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DUAL-USE APPLICATIONS OF INFRARED SENSITIVE MATERIALS

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High performance infrared focal plane arrays made from sensitive materials such as me as mercury cadmium telluride grown on a substrate of cadmium zinc telluride have been proposed for use inan extensive variety of military equipment for over a decade, ranging from early-warning satellites to missile seekers. In this report, we describe and quantify the potential dual-use markets for such detectors.

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## Executive Summary

High performance infrared focal plane arrays (IRFPAs) made from sensitive materials, such as mercury cadmium telluride (MCT) grown on a substrate of cadmium zinc telluride (CZT), have been proposed for use in an extensive variety of military equipment for over a decade, ranging from early-warning satellites to missile seekers, and from shipboard search and track systems to weapon sights. Despite their successful application to military problems, however, second generation, photovoltaic IRFPAs have not yet found widespread uses in commercial markets. This is not for a lack of ideas about how they might be used; concepts for their commercial application abound in scientific literature and in the discussions of officials of companies which manufacture infrared devices based on older technologies. Rather, the high price of contemporary IRFPAs, combined with differences between some of the characteristics of such devices intended for military purposes and those which would be suitable in commercial ventures, have slowed their introduction into commercial marketplaces.

In 1991, the Advanced Research Projects Agency (ARPA) contracted with a consortium of firms led by Johnson Matthey Electronics to undertake a variety of measures intended to reduce the cost of infrared sensitive materials. Greater use of such materials in commercial markets could contribute to this goal indirectly by facilitating the economies of scale typically made possible by higher volume manufacturing processes. More directly, the development of many potential commercial applications of IR sensitive materials could benefit the Defense Department by improving the quality of products it purchases from commercial vendors and, over the long term, by reducing their cost. As has been demonstrated persuasively in the case of semiconductors, advances in military technologies and commercial applications of these technologies are synergistic -- contributing to higher performance and lower costs in both the commercial and defense sectors.

The three goals of this study are to describe potential dual-use applications for second generation, photovoltaic focal plane arrays, assess the major obstacles to widespread utilization of advanced IR devices in such applications, and describe priorities in a defense research and manufacturing support program that would aim to overcome those hurdles, yielding a technology with dual-use appeal. The study focuses on MCT-based focal plane arrays because they offer the greatest sensitivity, resolution, scan rate, and weight and size reduction, and could therefore offer the greatest performance of any IR sensitive material. Only commercial applications of some potential benefit to the Defense Department were included in the study.

We found over 200 potential dual-use applications of second-generation focal plane arrays, grouped into seven broad areas of application, namely:

- <u>Biomedical thermography</u>, in which sophisticated IR detectors could passively and quantitatively image pain, neurological damage, inflammation, or increased local metabolism which is an indicator of cancer, vascular damage or healing;

- Non-destructive evaluation, in which integrated circuit boards could be thermally assessed for damage or faulty manufacturing, advanced composites and materials could be tested for defects, buildings and structures could be monitored for leaky insulation, roofs scanned for moisture damage;
- Predictive maintenance, in which industrial plants, factories, nuclear power plants, electric power generator facilities and foundries could thermally inspect mechanical and electrical equipment for early detection of wear or impending failure;
- Process control, in which IR machine vision systems could automate welding, inspect the myriad of metal, rubber, plastic and textile sheets which emerge from web production lines, monitor heat changes in wafers, chemicals, and rigid injection molded plastic and metal components;
- Remote sensing, in which IR detectors could be used for scientific research such as geological and crop assessments, imaging underground objects such as contaminated and toxic waste, aquifers and archeological sites, for environmental crisis evaluations of oil spills and fires, and in gas leak detection in factories and pipelines;
- Surveillance, in which IR cameras could endow airborne and ground-based police with night vision during search and rescue missions and law enforcement operations, and in counternarcotics reconnaissance where they could help detect indoor drug growing and processing plants, underground stashes and chemical traces of drug processing; and
- Transportation, in which IR detectors could be placed in passenger cars, trucks, buses, or trains to enhance drivers' vision during darkness, rain, fog, or other obscurants, help in collision avoidance, and help passenger, cargo, and corporate jets see through darkness, fog, mist, clouds, and rain, as landing and navigation aids.

All told, these commercial markets could reach a total value of $2.2 billion annually in about five years. MCT-based IRFPAs would be most likely to be used in ten specific applications: monitoring of heat changes and material "webs" in manufacturing processes; predictive maintenance of electrical and mechanical parts; inspection of integrated circuit boards; non-destructive evaluation of advanced materials and composites; biomedical thermography; surveillance; enhanced vision systems for airplanes; underground remote sensing; and environmental crisis assessment. In each of these market segments, potential customers will demand the very high performance standards that can be met best by MCT-based arrays, and are willing to pay the relatively high prices necessary to achieve them. In other dual-use sectors, such as automobile drivers' vision enhancement, the acceptable cost of IR systems is so low as to all but exclude MCT-based systems for many years.

A major hurdle in the realization of any of these commercial markets is that the characteristics of IR detectors demanded for commercial applications differ significantly from those required by the Department of Defense for military purposes, most notably in cost, which must be vastly lowered. The performance characteristics demanded for each of the dual-use categories of application are listed in the table below. The next-to-last column of the table specifies the threshold price of IR systems which potential users told us would be acceptable for a substantial number of users in their industry. The final column estimates the total annual market value for each area of application, based on feasible unit prices and estimated numbers of units that could be sold annually.

The federal government could take a number of steps to aid the commercialization of second generation IRFPAs, mainly by encouraging steps that would reduce their cost. These include:

- Sponsor research that could result in less expensive cooling components;
- Revitalize research in detectors operating in the mid-wave infrared (3-5 microns);
- Continue fundamental producibility research for MCT-based detectors;
- Develop integrated packages of all auxiliary components in IR detectors;
- Increase production rates of IR sensors for military equipment, thereby making possible economies in manufacturing processes;
- Standardize second generation detectors in a manner similar to the Common Modules in the 1970s and 1980s; and
- Reduce excessively demanding military specs such as testing and operability requirements.

Commercial applications of IRFPAs would not only aid American industry, but also would benefit the Department of Defense, both by making possible higher performance for many processes and products utilized by the Department and by lowering the cost of advanced IR sensors used in military equipment. The commercial adaptation of advanced IR systems is consistent with the nation's economic and security interests.

## Detector Characteristics Desired for Commercial Applications

| APPLICATION | IMAGE SIZE | SENSITIVITY | SCAN RATE | RANGE | RADIOMETRIC | POTENTIAL FOR MCT-BASED | FEASIBLE UNIT PRICE | MARKET VALUE |
|---|---|---|---|---|---|---|---|---|
| Biomedical Thermography | Large Area 2-D | <0.1°C | >60Hz | <5 ft | ✓ | High | \$50,000 | \$300 million |
| Non-Destructive Evaluation | | | | | X | | | |
| IC Board Inspection | Video Resolution 2-D | >0.1°C | 60 Hz | < 1 ft. | X | High | \$60,000 | \$240 million |
| Buildings & Structures | Video Resolution 2-D | 1-2°C | 30 Hz | 10-100 ft. | X | Low | \$20,000 | \$20 million |
| Materials for Defects | Video Resolution 2-D | <0.1°C | 1 MHz | 1-10 ft. | ✓ | High | \$50,000 | \$25 million |
| Predictive Maintenance | | | | | | | | |
| Electrical | Video Resolution 2-D | 0.1°C | 30 Hz | 1-20 ft. | ✓ | High | \$80,000 | \$400 million |
| Mechanical | Video Resolution 2-D | 0.1°C | 30 Hz | 1-20 ft. | ✓ | High | \$80,000 | \$400 million |

| APPLICATION | IMAGE SIZE | SENSITIVITY | SCAN RATE | RANGE | RADIOMETRIC | POTENTIAL FOR MCT-BASED | FEASIBLE UNIT PRICE | MARKET VALUE |
|---|---|---|---|---|---|---|---|---|
| Process Control | | | | | | | | |
| Weld Control | <100x100 | 0.1•C | 60 Hz | 1-5 ft. | ✓ | High | $75,000 | $23 million |
| Web Inspection | Linear (1x180+) | 0.1•C | 1.2 MHz | 1-2 ft. | X | High | $75,000 | $225 million |
| Monitor Heat Changes (chemicals, glass, plastics, metals, wafers) | Video Resolution 2-D | <0.1•C | 30 Hz | 1-10 ft. | ✓ | High | $75,000 | $188 million |
| Food Inspection | Linear (1x180+) | 0.1•C | 1 MHz | 1-2 ft. | X | Medium | $75,000 | $38 million |
| Remote Sensing | | | | | | | | |
| Scientific Research | Large Area 2-D | 0.1•C | <30 Hz | From space | X | High | $200,000 | $10 million |
| Underground (contaminated & toxic waste, graves, aquifers) | Large Area 2-D | 0.1•C | 30 Hz | 1,000-3,000 ft. | X | High | $50,000 | $20 million |
| Environmental Crisis Evaluation | Large Area 2-D | 0.1•C | 30 Hz | 1,000-3,000 ft. | X | High | $50,000 | $10 million |
| Pipeline & Gas Leaks | Video Resolution 2-D | 0.1•C | 30 Hz | 1,000-3,000 ft. | X | Medium | $50,000 | $30 million |

| APPLICATION | IMAGE SIZE | SENSITIVITY | SCAN RATE | RANGE | RADIOMETRIC | POTENTIAL FOR MCT-BASED | FEASIBLE UNIT PRICE | MARKET VALUE |
|---|---|---|---|---|---|---|---|---|
| Surveillance | | | | | | | | |
| Police (search & rescue, law enforcement) | Video Resolution 2-D | 0.1°C | 30 Hz | 100-1,000 ft. | X | High | $125,000 | $56 million |
| Counternarcotics Reconnaissance | Video Resolution 2-D | 0.1°C | 30 Hz | 1,000 ft.-6 miles | X | High | $125,000 | $25 million |
| Transportation | | | | | | | | |
| Driver's Vision Enhancer | Video Resolution 2-D | 0.1°C | 30 Hz | 1200 ft. | X | Low | $1,000 | $100 million |
| IVHS Components | Video Resolution 2-D | 0.1°C | 30 Hz | 1200 ft. | X | Medium | $10,000 | $10 million |
| Airplane Enhanced Vision System | Large Area 2-D | 0.1°C | 30 Hz | >2,600 ft. | X | High | $100,000 | $40 million |

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## Dual-Use Applications of Sensitive Infrared Materials

High performance infrared focal plane arrays (IRFPAs) made from sensitive materials, such as mercury cadmium telluride (MCT) grown on a substrate of cadmium zinc telluride (CZT), have been proposed for use in an extensive variety of military equipment for over a decade, ranging from early-warning satellites to missile seekers, and from shipboard search and track systems to weapon sights. Despite their successful application to military problems, however, IRFPAs have not yet found widespread uses in commercial markets. This is not for a lack of ideas about how they might be used; concepts for their commercial application abound in scientific literature and in the discussions of officials of companies which manufacture infrared devices based on older technologies. Rather, the high price of contemporary IRFPAs, combined with differences between some of the characteristics of such devices intended for military purposes and those which would be suitable in commercial ventures, have slowed their introduction into commercial marketplaces.

In 1991, the Advanced Research Projects Agency (ARPA) contracted with a consortium of firms led by Johnson Matthey Electronics to undertake a variety of measures intended to reduce the cost of infrared sensitive materials. Greater use of such materials in commercial markets could contribute to this goal indirectly by facilitating the economies of scale typically made possible by higher volume manufacturing processes. More directly, the development of many potential commercial applications of IR sensitive materials could benefit the Defense Department by improving the quality of products it purchases from commercial vendors and, over the long term, by reducing their cost. As has been demonstrated persuasively in the case of semiconductors, advances in military technologies and commercial applications of these technologies are synergistic -- contributing to higher performance and lower costs in both the commercial and defense sectors.

Consequently, as part of the Johnson Matthey consortium effort, this study was initiated to identify the commercial applications in which IRFPAs would have potential, and to describe the steps necessary to overcome the barriers to realization of that potential. Given DoD's sponsorship of the effort, we have concentrated particularly on those applications with "dual-use" potential, ie. those which would benefit both commercial activities and contribute directly to improved products used by the Defense Department. The term is used broadly. If advanced IRFPAs could contribute to more efficient maintenance of structures made of advanced composites and materials, for example, such as aging aircraft, they would have obvious benefits for both the commercial aerospace sector and for DoD. But if IRFPAs also could be used to make possible more efficient manufacturing of integrated circuits (ICs), that, too, would benefit commercial activities and, indirectly, the Department of Defense by lowering the cost of ICs used in military equipment.

The three specific goals of the study are to:

(i) Identify and elucidate potential dual-use applications of advanced infrared devices based on these materials;

(ii) Assess the major obstacles to the widespread utilization of these materials in such applications, including, among other things, considerations of costs, detector requirements, cooling requirements, packaging, and collateral technologies; and

(iii) Describe priorities in a defense research and manufacturing support program that would aim to overcome these obstacles to yield an infrared detector technology with dual-use appeal.

We found over 200 potential dual-use applications of second-generation focal plane arrays, grouped into seven broad areas of application. IRFPAs could be essential components in systems used in a diverse range of industries from metallurgy to microelectronics to aerospace to paper milling. In some cases, focal plane arrays could revolutionize pre-existing applications of IR devices by improving cameras' resolution, sensitivity, and scan rate; applications in biomedical thermography and the predictive maintenance of electrical and mechanical equipment would have this character, for example. In other instances, IRFPAs could make possible completely new applications, such as automated welding, process control of metal, paper, and plastic web production lines, and enhancement of the vision of drivers of a variety of vehicles. By the late 1990s, commercial sales of advanced IR systems could reach a total market of over $2 billion.[1]

We also found, however, that it is far from certain whether current military programs developing second generation focal plane arrays alone would result in IRFPA technologies with the ability to fulfill this dual-use potential. This uncertainty exists despite the fact that military development and procurement plans are very ambitious for second generation IRFPAs, as is discussed in Appendix A. The problem is not one of scope, but of direction. There is potential to refocus research and development programs to shape the technology more appropriately for dual-use applications. New federal R&D programs, or modifications of existing programs, are necessary to overcome the deficiencies of current infrared imaging systems as they are perceived in the commercial market. A critical factor, obviously, is cost. Commercial companies manufacturing infrared cameras are eager to use second-generation focal plane arrays, but find

[1] By comparison, current US military programs would lead to a $6 billion market in the 1990s; these plans are unlikely to be fulfilled, however, with, among other things, the curtailment and redirection of the Strategic Defense Initiative to focus on theater defense. Realization of the $2 billion commercial market presumes a significant reduction in IRPFA costs, moreover, which, in time, would mean that the cost of military systems would also decline.

the components several times more expensive than would be acceptable to their customers. As a result, less capable, but far less expensive uncooled infrared detectors, such as those based on pyroelectric technologies, could fill some of the commercial applications that were identified.

In the conclusion of the study, we recommend seven feasible steps through which government research and manufacturing support programs could help to develop a more versatile, dual-use IRFPA technology. Creating such a technology is a matter of both identifying and targeting the commercial niches for IRFPAs with the greatest potential, and encouraging technological breakthroughs which make IRFPAs more affordable and technically desirable for commercial users.

This report is divided into three main sections in which each of these themes is developed more fully. The first section describes the scope of the study and the methodology which was used. The second section, the heart of the study, contains a comprehensive description of potential commercial applications of advanced infrared devices, which would also benefit the DoD. The third section presents our conclusions about this commercial potential overall, the major technological obstacles to be overcome if advanced IR detectors are to fulfill their dual-use potential, and the elements of a federal program intended to overcome these barriers. The report is supplemented by fourteen appendices describing the content and sources of our information, as well as related material.

## Part One

## Approach

This study of future applications of infrared sensitive materials has been based on published materials, on separate surveys of companies engaged in IR commercial development and of individuals working on IR problems at universities and non-profit organizations, on in-depth interviews with researchers and executives of commercial firms, federal agencies, and defense manufacturing companies, and on telephone inquiries to more than 350 individuals at companies that could potentially use IR devices in their work. Because of the rapid changes in IR technologies, we found that published sources lagged considerably in describing the state of the art. Moreover, given that most of the more interesting developments are taking place in the profit-sensitive private sector, there is a reluctance to publish and share ideas with a wide audience. As a result, we found telephone inquiries to be the most useful source of information. When using such information, we always insisted that information be corroborated by at least two independent sources.

Even so, many, if not most, of the conclusions in this report must be considered subjective. This is true, particularly, of the estimates of market size for various potential applications, as well as the detail contributing to such judgments as the feasible cost of the IR systems that would make possible each application. Market forecasting is hardly an exact science, particularly as concerns the introduction of new technologies. Recognizing the subjectivity of the report's conclusions, we have tried to be conservative in our judgments, erring on the side of smaller markets, lower feasible costs, and delayed introductions.

### Scope

The study focused, in particular, on sophisticated, photovoltaic infrared focal plane arrays based on MCT grown on a layer of CZT. Second-generation IRFPAs offer the greatest performance of any infrared detectors designed to date. Their sensitivities, scan rates, weight, size, uniformity, and pixel operability are all designed to exceed the capabilities of older military systems, and the defense community is keenly interested in prospective dual-use applications. Moreover, second generation MCT-based IRFPAs are undergoing extensive producibility research and development, and beginning to move into low rate initial production in a few military programs, so programs could still be modified at this early date to develop focal plane array technologies with a dual-use capability. The time is right, therefore, to explore potential dual-use applications for photovoltaic focal plane arrays.

In considering potential dual-use applications of IRFPAs, we analyzed both detectors optimized for the long-wave infrared (LWIR) 8-12 micron window, and those designed for the mid-wave infrared (MWIR), 3-5 micron window. Detectors operating in the near infrared (NIR), despite promising potential, were not included in this study because MCT-based detectors can not operate below two microns, and do not operate in the NIR. Likewise, applications which would require infrared detectors with spectral ranges beyond 12 microns were not considered because they would exceed MCT's range.

Similarly, dual-use applications of both linear and two-dimensional staring arrays are included in the study. Older infrared technologies, such as single point systems, photodiodes, photocapacitors, and photoconductive scanning devices such as SPRITE-style detectors, differ fundamentally from photovoltaic MCT-based IRFPAs, have already been introduced into commercial products, and therefore are not included in the study.

The study did not directly explore the commercial potential for IR detectors based on other IR sensitive materials, such as indium antimonide (InSb), platinum silicide (PtSi), gallium arsenide (GaAs), extrinsic silicon, or lead salt materials. These materials are not expected currently to reach the mixture of technical sophistication, high performance, and eventual low-cost of MCT-based IRFPAs. However, as the central purpose of the study was to assess the potential for MCT-based IRFPAs to fill prospective commercial applications, it was necessary to compare the advantages and disadvantages of MCT-based detectors with those based on other materials in specific applications. Uncooled ferroelectric infrared detectors are a particularly promising technology for many of the less sophisticated applications, and are addressed specifically in Appendix B.

Generally speaking, all significant dual-use applications which reasonably could be met by the varieties of MCT-based infrared focal plane arrays now being developed by DoD are described in part two of the study. Several prospective applications are not included in the final report because they are limited in scope and market potential, or would not even potentially use sensitive infrared detectors. For example, some have suggested the use of advanced detectors to tune lasers. If laboratories had both lasers and infrared detectors, they might use them in conjunction, but labs would most likely not purchase IR detectors solely to tune their lasers.

A family of low-technology applications unlikely to employ sophisticated MCT-based detectors are those which require point radiometers. These inexpensive, non-contact photodiodes sense the temperature of objects ranging from molten metal to baked foods, but it is extremely unlikely that more sophisticated or mosaic detectors would be demanded by end-users; single point readings are sufficient for their needs. Another family of applications not discussed because only lower-performance IR detectors would be demanded are automated spectral-analyzers, such as Fourier-Transform IR detectors (FTIR). Since the vast majority of FTIR spectrometers do not need to image any faster than video speed, and are only needed to give point readings, they would not require focal plane arrays, although smaller, lower quality wafers of MCT or CZT would work well.[2] Finally, some applications had so little defense relevance, such as mapping of human neurons or mapping the solar surface, that they were excluded from the study.

Databases

Four databases were created as part of the study: an annotated bibliography, a list of government and private organizations carrying out research on applications of infrared materials, a list of professional and trade associations serving the infrared community, and a list of individuals carrying out research on applications of sensitive infrared materials.

Annotated Bibliography. Appendix C contains the bibliographic database, covering material published during the past five years which describe potential commercial applications of advanced IR systems and developments in relevant technologies. The entries were gathered systematically through a number of commercially available and private bibliographic sources. Research was conducted at the Library of Congress, the National Institute of Standards and Technology, and several university libraries in Washington, D.C. Some of the commercial databases searched were ProQuest, WorldScope, ABI/Inform, PAIS, Predicast, DIALOG, and Econlit. Bibliographic searchers also were conducted by the Defense Technical Information Center (DTIC) and the Infrared Information Analysis Center (IRIA). Some of the trade associations which maintain private databases, and which conducted searches for this study, include the International Society of Optical Engineering (SPIE), the Institute for Electrical and Electronic Engineers (IEEE), the Optical Society of America (OSA), the Society of Manufacturing Engineers (SME), Palisades Institute for Research Services, and the American Institute of Chemical Engineers. A number of sources were culled from specialized professional societies, such as the American Iron and Steel Institute, American Paper Institute, American Society for Metals, American Society for Testing and Materials, American Society for Photogrammetry and Remote Sensing, Electrical Power Research Institute, American Society for Nondestructive Testing (ASNT), and the American Society for Quality Control. Numerous journals which cover electro-optics were searched specifically, including Photonics Spectra, Laser Focus World, Microwaves and R/F, P/PM Technology, Process Control, Automated Inspection, and Maintenance Technology. Another valuable resource was referrals from individuals who were contacted during the course of the study, particularly for articles in such trade journals as Materials Evaluation, Engineer's Digest, Water Engineering and Development, and Forest Industries.

[2] Notable exceptions to the usually low-tech spectral analysis fields include remote sensing for scientific research, gas and leak detection, and aerial surveillance for specific contraband and tracer chemicals, and illegal plant species, all of which are discussed in part two of the study.

The annotated bibliography contains 450 articles, filed into ten categories:

(i) basic scientific primers;
(ii) overall trends in IR materials;
(iii) trends in other IR components;
(iv) applications in biomedical thermography;
(v) applications in non-destructive evaluation;
(vi) applications in predictive maintenance;
(vii) applications in process control;
(viii) applications in remote sensing;
(ix) applications in surveillance; and
(x) applications in transportation.

Private Organizations Carrying Out Research on Applications of IR Materials. Appendix D contains a listing of private companies and universities believed to be engaged currently in relevant research on all types of advanced infrared devices. These organizations have been identified through several sources, including the Directory of American Research and Technology -- 1992, the Federal Laboratory and Technology Resources Directory, produced by the Department of Commerce, Laser Focus World's 1992 Buyer's Guide, DTIC and IRIA searches, and several trade associations, most importantly SPIE, IEEE, SME, and ASNT. We also came across several small businesses working on infrared applications through referrals from individuals we had contacted for interviews.

Five hundred ninety-six firms engaged in infrared research are listed in the database. Two hundred forty are engaged primarily in defense-related infrared work, but may be interested in commercial applications; two hundred sixty operate primarily in the commercial marketplace. Ninety-six are university research centers engaged in IR research. We included firms in the database regardless of the level of their infrared work, including companies working on substrate growth, epitaxial growth, array fabrication, auxiliary components, applications development, systems integration, and IR camera sales. We also included several major consulting companies that conduct thermographic inspections and non-destructive evaluations. These companies are essentially end-users of IR devices, but also have a large say in the types of commercial infrared systems which are developed.

Professional and Trade Associations Serving the Infrared Community. This component of the database, presented in Appendix E, combines organizations that both deal directly with infrared developments, applications, and producers (such as the SPIE and IEEE), and end-user societies, whose main focus is serving the industries that would be primary users of infrared devices, such as the American Paper Institute or American Society for Metals. Fifty-seven organizations are listed and described in this database.

Individuals Carrying out Research on Applications of Sensitive Infrared Materials. This component of the database is presented in Appendix F. For the most part, it has been derived from the other three. The individuals listed fall into several categories: engineers and scientists, marketing directors and other sales representatives, other company executives, journalists, and private consultants. Nine hundred eighty-three individuals are listed in the database.

Methodology

The individuals listed in the fourth component of the database provided the basis for selecting 207 individuals working at the firms judged to be the most actively interested in developing applications of focal plane arrays. A written questionnaire was sent to each of the individuals. There were 120 recipients in industry and 87 at university research centers. Through repeated follow-up phone calls, about 35 percent of the recipients were induced to respond, either by written comments or dictated replies. Although relatively low, this number is not atypical of such inquiries to industry. Nineteen of the respondents were contacted for in-depth interviews because they had reported unique commercial applications which integrated MCT-based infrared detectors, or because they had demonstrated a clear understanding of the technical obstacles to be overcome.

Copies of the questionnaires, which solicited opinions on potential applications of advanced IR detectors and the barriers to their use, are included in Appendix G. Slightly different questionnaires went to the industry and university sectors, the former focusing on commercially viable applications, the latter on technological barriers to be overcome to develop a dual-use technology. Although informative, the surveys proved not to be the most useful element in the overall pool of resources, with in-depth interviews, telephone inquiries, and published sources playing more central roles. Responses to the questionnaires served mainly to identify those individuals and firms with particular interest in the development of infrared technologies for commercial purposes.

Separately from the surveys, more than 350 individuals were contacted by telephone during the main analysis phase of the study to discuss potential commercial applications of advanced IR systems. These individuals were identified either from published materials, trade societies, commercial infrared firms, military contractors engaged in infrared research, university centers, or referrals. The individuals contacted include executives of commercial IR companies, as well as their engineers, marketing managers and sales representatives, end-users, system integrators, executives of military contractors considering commercialization of infrared technologies, along with their sales representatives, strategic planners, engineers, and scientists, trade association executives, and individuals at infrared thermography consulting firms. The specific individuals who provided valuable information for each broad area of application are listed in appendices to each of those sections. The ground rules for our conversations specified that individuals could be listed as participating in these conversations, but not be associated with any particular conclusion or judgment.

Ideally, we sought to identify the emergence of a clear consensus among informed individuals concerning the most likely commercial applications of MCT on CZT during the next decade, as well as the barriers to fulfillment of this potential. In cases in which individuals or published materials offered conflicting positions, we present all views, as well as the basic reasons for the dispute. In most cases, however, sources converged on both potential applications and the barriers needed to be overcome.

In general, the individuals we interviewed were interested in discussing the particular applications with which they were familiar, rather than offering a broad overview of the field; this might help to explain the reluctant response to the written questionnaires. We found no one individual, or small group of individuals, who could name all seven areas of potential application for IR detectors, let alone list the specific applications in all categories. For example, there appeared to be considerable overlap among individuals familiar with predictive maintenance applications and those in non-destructive evaluation, but individuals in the biomedical, surveillance, and transportation sectors were typically unaware of efforts underway in other areas of application for IR devices, and vice versa. This may be evidence of segmentation within the commercial infrared imaging market or simply a symptom of the caution with which commercial firms approach potential new developments.

Once a clear picture of potential applications of MCT-based infrared detectors was attained, we assessed the relevance of each process for the production of defense equipment, or for the provision of services utilized by the Department. In many cases, of course, the identified process was applicable to such a wide range of industries that the question of defense-relevance was easily resolved; for instance, thermographic inspection of machinery and electrical equipment, and the non-destructive evaluation of advanced materials or engine components using IR techniques. In a few cases, however, specialized applications would be of only limited relevance to the Department of Defense. For instance, automated food inspection utilizing IR systems could decrease the cost or improve the quality of food purchased by the Department, but would, of course, not have a major impact on the Defense program.

For each prospective commercial application of advanced focal plane array technologies that would be of at least marginal benefit to the Department, we endeavored to answer the following questions:

1. How would IRFPAs be integrated specifically into such an application?

2. What specifically would be the desired:
    - imaging wavelengths;
    - array sizes;

- speeds of image acquisition;
- sensitivity;
- radiometric qualities, if necessary;
- cryogenic needs; and
- auxiliary electronics?

3. Are infrared devices currently available for the application, or are they now being developed? If so, which companies are carrying out the work?

4. What obstacles remain to be overcome?

5. If the technical obstacles could be overcome, at what price would end-users be willing to utilize advanced IR systems? At these threshold prices, how many systems might be sold annually?

6. Given the current state of the field, how long might it take for advanced IR systems to begin filling this market niche?

7. What is the potential for sensors based on non-IR technologies to fulfill the need identified previously? How about IR sensors based on materials other than MCT? Could less expensive IR sensors such as those utilizing InSb, PtSi, the lead salts, or ferroelectric materials perform adequately for the commercial needs that had been identified?

8. Finally, which component suppliers and system integrators are currently seeking to fulfill the commercial needs that have been identified, and what products are they offering? What are their strengths and weaknesses?

Specific applications were not included in the report unless three independent sources confirmed their potential. Although companies' reports and advertising were used as background, they were not considered authoritative in judging the potential for particular applications. This strategy was implemented because it became clear that in certain market sectors, specifically biomedical thermography, predictive maintenance, and remote sensing, more moonshine than scientific rigor has sometimes gone into the promise of applications. Direct conversations with researchers, engineers, or marketing directors actively engaged in putting an IR device on the market were essential in determining the potential of each application. Moreover, we insisted that at least two individuals not directly involved in the application corroborate the general descriptions and judgments about a promised application before it could be included. In most cases, end-users also were contacted and asked to corroborate the promised application. Although most commercial infrared manufacturers keep lists of potential end-users proprietary, for obvious reasons, it was possible, in almost all cases, to identify and contact end-users directly, by other methods.

The report concludes by highlighting the most promising areas of dual-use application for MCT-based second-generation IR systems, and by describing the obstacles to fulfillment of this promise. Insofar as cost appears to be the overriding obstacle, we recommend seven means through which federal research and manufacturing support programs could help to encourage the development of lower cost IRFPAs suitable for use in relevant dual-use sectors. In preparing these recommendations, we were mindful of budgetary and other constraints on federal programs.

The closing section of the report summarizes the implication of the recommendations for federal technology policy.

## Part Two

## Applications

There are seven broad, dual-use areas of application for second generation, infrared focal plane arrays: biomedical thermography, non-destructive evaluation, process control, predictive maintenance, remote sensing, surveillance, and transportation. Many of these broad applications, in turn, can be subdivided into two or more specific sub-categories of application, depending on the characteristics of the systems that would be most useful or the structure of the specific market segment. Categories and sub-categories of application are listed in table one and described in this section.

**Table 1. Categories and Subcategories of Dual-Use Applications for Second Generation IRFPAs**

| Category | Sub-category (if any) |
|---|---|
| Biomedical Thermography | |
| Non-Destructive Evaluation | |
| | IC Board Inspection |
| | Buildings & Structures |
| | Materials for Defects |
| Predictive Maintenance | |
| | Elecrical |
| | Mechanical |
| Process Control | |
| | Weld Control |
| | Web Inspection |
| | Monitoring Heat Changes (chemicals, glass, plastics, metals, wafers) |
| | Food Inspection |

| Category | Sub-category (if any) |
| --- | --- |
| Remote Sensing | |
| | Scientific Research |
| | Underground (contaiminated & toxic waste, graves, aquifers) |
| | Environmental Crisis Evaluation |
| | Pipeline and Gas Leaks |
| Surveillance | |
| | Police (search & rescue, law enforcement) |
| | Counternarcotics Reconnaissance |
| Transportation | |
| | Driver's Vision Enhancer |
| | IVHS Components |
| | Airplane Enhanced Vision System |

## Biomedical Thermography

Infrared detectors have a wide range of potential applications in the diagnosis of diseases and in monitoring their treatment. The benefits of the technology were overstated when it was first introduced, however, and the medical community is now skeptical of its value. Viewed as a secondary and corroborative diagnostic device at present, thermography is not yet accepted by the medical insurance industry as a necessary technique- a crucial hurdle to be overcome if the market's potential is to be fully realized. Even so, we project a market totaling $300 million per year before the end of the decade.

In this section we analyze the prospective use of infrared detectors in biomedical diagnoses. We discuss the basic theory behind infrared thermography, and compare the IR approach to medical diagnoses with its competitors. We then introduce the two basic varieties of thermographic techniques that can be used for the diagnosis of pathologies, each of which require different system designs, and offer an exhaustive list of current and future application. We then discuss the specific prerequisites for biomedical applications as seen by the thermography community to move forward. Japan's significant progress in, and widespread use of, infrared imagers is also discussed, because the Japanese model might well foreshadow the American market. Finally, we describe the size and structure of the prospective market for biomedical thermal imagers and conclude by discussing the US companies working on thermography detectors and system designs. Appendix H contains the names and affiliations of several the individuals who were interviewed for this section.

Technology of Biomedical Thermography. Infrared thermography has been used since the early 1960s as a medical diagnostic technique to profile skin temperature up to 2mm beneath the surface. The method is completely non-invasive and does not require illumination, consumption of injection of isotopes, etc., since infrared detectors are passive. There are no side-effects whatsoever from passively sensing skin temperature, which means there is no limit to how frequently or for how long the infrared detector system could be employed.

According to thermography's substantial number of proponents, skin temperature contains copious clinical data which can be invaluable in medical diagnoses. These include information about **metabolic rates** under normal or feverish (febrile) conditions, about **perfusion** (overabundance of blood flow) to certain regions of the skin that reflect the blood supply to the deeper, underlying tissues, about **neurological control** of skin level (cutaneous) blood flow that reflects the functioning of the sympathetic nervous system, about local irritation or **inflammation**, and about cutaneous local **parasitic** or **tumorous** (neoplastic) lesions. Reliable temperature profiling, which is the gist of clinical thermography, can be used in both the diagnosis and management of these and other disorders.

Thermography differs from its competitors, namely Magnetic Resonance Imaging (MRI), Computer Aided Tomography (CAT) scans, radiology, and ultrasound, in that it images *function* rather than *structure*. This is its chief competitive advantage. Ultrasound and radiology, for instance, reveal the body's internal structure of muscle, skeleton, and organs, but tell very little about how those tissues are functioning. By contrast, thermography reveals the *function* of the tissue being imaged, as shown by its temperature profile, which is a consequence of metabolic rate, blood flow, and inflammation (if any). In the case of mammography, for example, x-rays are traditionally used to image structures under the skin which may be cancerous. But IR thermography can be used in the same application, not to measure or detect cancer per se, but rather to quantify its physiological effects, which are the increased metabolic rate in a particular region, resulting from local inflammatory skin reactions and/or dilation of subcutaneous breast veins. IR thermography can even improve on a radiologist's diagnosis when breast cancer is found. Absolute temperature readings of such tumors is very beneficial in determining the rate of growth of the cancer and in drawing a prognosis, since "hotter" tumors correlate with greater mortality rates.

Thermography is virtually the only potential technique for diagnosis in several of the applications listed below, since some diseases result in arteries, veins, or hyperactive or underactive tissues emitting heat profiles that are atypical or that differ from their surrounding areas, without any change in the underlying structure or shape of the bones, muscles, or organs. Therefore, thermography offers potential advantages to biomedical diagnoses.

In early thermography systems, diagnosticians had to evaluate thermal images in pseudo-color visually to identify abnormalities in skin temperature. These early systems were based on a technique called "contact thermography," and had no multiplexing or hybridization to digitize the data; the picture was simply viewed by the clinician. This led to both false positives (ie. finding pathologies where there was none) and false negatives (ie. not finding pathologies where there was indeed one). This sort of *qualitative*, rather than *quantitative* system, was used in early mammography experiments, which largely failed and undermined the credibility of infrared thermography in the US in the 1970s. The performance of radiometers, which were the successor technology, was not much better. Those systems continued to scan slowly, had poor resolution, and were unreliable.

The absolute, quantitative assessments of temperature gradients over large areas, however, would permit detailed, accurate, and reliable diagnoses. And in the last few years, such systems have been developed based on 1970s-vintage military infrared technology. The detectors use single pixels or simple linear arrays, based on either Indium Antimonide (InSb) or MCT. They are either SPRITE design or linear scanning units; no model is on the market which uses a staring detector. However, MCT-based arrays offer substantial advantages over InSb-based arrays because of their ability to determine absolute temperature in each pixel over the field of view. This is beneficial to the thermographer, who can then perform three types of statistical comparisons of temperature: first, differences in average temperature between two areas across, say, a line of anatomic symmetry, can be evaluated statistically to establish the *significance* of that deviation. Second, hot or cold spots can be recognized by evaluating the temperature gradients around them, looking for statistically significant differences between adjoining regions in the scan. A third, but so far immature technique, would be to have a computerized pattern recognition system identify pathologies quantitatively. MCT-based arrays, which have the potential to determine absolute temperature specifically, are the best technology that can collect the data necessary for these kinds of precise diagnostics.

Two Varieties of IR Thermography Systems. Depending on the pathology, two different infrared thermography techniques can be used, requiring two different system designs and detector figures-of-merit. The two techniques are Dynamic Thermography and Absolute Temperature Thermography.

Dynamic Thermography (DT) is used to determine fluctuations in skin temperature over a *span of time*, whether a half hour during which medicine is being monitored for its effect on a patient, or several minutes while viewing hands as they reheat after being exposed to cold, for instance. Through hundreds of snapshots, a "movie picture" of the thermal flow in a particular region can be generated. DT is less concerned with ascertaining absolute temperatures than it is with drawing *comparisons*, between a region and its adjoining area, and within the same region of study (ie. a blood vessel, a nerve, a tumor, etc.) over a span of time. But the most advanced dynamic systems, according to those surveyed, will be able to assess absolute pixel temperatures in real-time, rather than just draw comparisons. For example, the time series of temperature measurements can undergo "Fast Fourier Transform Analysis" to yield a power spectrum of the temperature gradients in that region. Certain degenerative diseases, especially neurological disorders, lend themselves to DT because they progressively curtail the blood flow to the affected region, cooling the tissues over time. A great variety of pathologies can be diagnosed by comparing sides of the body for significant temperature differences, such as back injuries, musculoskeletal damages, and vascular disorders in limbs. As in other neurological or neuromuscular tests, e.g. Electro-cardiograms (ECGs) or Electro-Myograms (EMG), substantial diagnostic information is embedded in the dynamic behavior of the system, which requires temporal study to draw a reliable diagnosis.

DT is a very demanding technique. It requires highly precise measurement of infrared flux (<0.001°C), and both short-term and long-term stability (<0.00005°C equivalent of electronic or thermal noise and a drift of <0.01°C/hr). These requirements are within the range of the IR detectors now under development by the US military.

The other form of biomedical thermography is Absolute Temperature Thermography (ATT). Instead of comparing temperatures as dynamic thermography does, ATT measures the precise temperatures of each pixel in an image.[3] Data can be analyzed as a picture or the raw temperature data can be analyzed for abnormalities that are statistically significant. This technique is quite naturally the one in which MCT-based systems would be immediately useful, as they offer an ability to measure absolute temperatures.

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[3] See, for example, M. Anbar "Computerized Thermography: The Emergence of New Diagnostic Imaging Modality," Intl J. of Technology Assessment in Health Care (1987:3) pp. 613-621.

Researchers developing ATT are tending increasingly to profile the skin simultaneously in several wavelengths with an array of several detectors, each in a different range of the infrared. Previous researchers had been treating the skin as a black body, assuming it had a uniform infrared emissivity and reflectivity over its entire surface. But in reality, the emissivity of skin is lower than 100 percent in the infrared, and fluctuates several percentage points around curves and due to irregularities. Therefore, absolute temperature readings are not reliable with just one detector centered around one wavelength. ATT requires a system which can sort through those "extraneous" factors. The new multidetector scheme allows absolute temperature to be calculated alongside emissivity at each point of the image. One researcher, for example, recently profiled in four wavelengths simultaneously -- with cutoffs of 4.3, 6.5, 10.6, and 15.3 microns -- using linear MCT-based arrays.[4] This system appears to overcome the previously formidable barrier of separating the emissivity readings of skin from its absolute temperature. Specific uses are in comparative studies of sides of the body for abnormal neurological, sympathetic pain, or vascular conditions, and in "snapshots" of body temperature in cancer research and ophthalmology.

Applications. Thermography is believed by many to be capable of making significant contributions to medical diagnoses in ten broad fields. Systems have already been fielded for clinical study in five of those areas: vascular disorders, neurological disorders, sympathetically maintained pain, arthritis (and rheumatism), and tissue viability. The other five areas of application are still experimental but garnered much support from those interviewed: oncological disorders, neonatal pathologies, dermatological disorders, ophthalmology, and surgery.

1. Thermography has been recognized from its inception as a valuable diagnostic tool for **vascular disorders**, such as deep venous thrombosis or occlusion of the carotid arteries. Since veins run close to the skin, they directly affect skin temperature, which can be measured by an IR detector. For example, thermography can play a role in the diagnosis of deep vein thrombosis in the extremities, and to distinguish between such a disorder and the simple venous insufficiency associated with varicose veins. Deep vein thrombosis can be diagnosed quicker and more accurately than by phlebography, the most accurate competing technique. The thermograms of a resting healthy patient, for example, would show calves and thighs to be cool, with the subcutaneous border of the tibia and patella cooler than the surrounding muscle. But in deep

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[4] See S. Hejazi et. al., "Scope and Limitation of Thermal Imaging Using Multi-wavelength Infrared Detection" Optical Engineering (November 1992) pp. 2383-93. or S. Hejazi "A Thermal Imaging System Based on Multi-Wavelength Infrared Detection" Doctoral Dissertation, State University of New York at Buffalo (1990).

vein thrombosis, there is a diffuse increase in calf temperature to about 2°C, which is easily picked up by the thermogram[5]. By contrast, a superficial varicose vein's serpentine course can be seen in thermography much better than by ultrasound, the competing technique. Ideally, the system would be used either alone or as a first- screening method before resorting to venography, which is much more expensive and is associated with significant morbidity.

Thermography can be used to diagnose Raynaud's disease, in which the blood supply to the extremities, such as the nose, ears, fingers, and toes, is virtually cut off when exposed to cold temperatures. After a cold stress test, the limbs are observed as their temperatures rebound, but remain colder for much longer in Raynaud's sufferers. Thermograms can assess the severity and locate the precise regions affected by the disease, and assess the regions' response to drug therapy.

Thermography can document abnormally increased arterial blood flow and associated alternate vascular pathways. It has been judged better than other non-invasive tests in identifying collateral facial and supraorbital branches of the external carotid artery in the presence of internal carotid stenosis (ie. narrowing of the arterial passage). Thermography can also document increased venous blood flow, in a scrotal varicocele, for instance. Hyper- and hypo- thermia have been very effectively documented with IR imagers, especially if it lies in extremities like fingers and toes. IR thermography is the best technique for imaging vascular disorders, according to the surveyed, because these disorder manifest themselves in skin surface temperature fluctuations. These sorts of anatomical and structural problems lend themselves best to Absolute Temperature Thermography, because the condition is static.

Although patients with these disorders are being diagnosed and monitored by recovery using thermography, what is lacking, according to those surveyed, is systematic database creation of how exactly the temperature profile changes during specific vascular disorders. It will be 3-5 more years to create databases of how the thermal profiles of patients with known vascular diseases change under their disorders. It will contribute significantly to diagnosis once norms and databases have been formed.

2. **Neurological pathologies**, which are primarily functional disorders, are best diagnosed by means of Dynamic Thermography, perhaps in conjunction with thermal stress. For instance, the extremely common clinical complaints of extremity and back pain are often associated with complex disturbances of the sympathetic nervous system, which also controls microcirculation of the skin. The physiological changes associated with extremity and back symptomatology is

[5]S.G. T.L. Burney, T.L. Williams and E.H.N. Jones "Applications of Thermal Imaging" (Adam Hilger:Philadelphia) 1988.

reflected in altered skin microcirculation and can be imaged by thermograms.

Thermography is particularly useful in imaging lumbar back pain, cervical spine pain, where it is considered by many interviewees to be superior to the MRI technique, lumbar disc herniation, cephalic degeneration, and myofacial (facial muscle) pain syndrome.[6] Results have been equal to, if not exceeding, those from Computer Aided Tomography (CAT) and enhanced myelography in detecting nerve fiber irritation (radiculopathy).[7] Spinal nerve root compression has been clearly demonstrated by thermography. Other applications with similar design needs are nerve root impingement, reflex sympathetic dystrophy (RSD), and other painful problems, such as myofascial injuries and stress fractures.[8] Most notably in RSD, it is hard to accurately diagnose the disease in its early stages, and the results of such tests as triple-phase bone scans are frequently normal. Thermography can not only detect RSD more effectively, but has also been found effective in monitoring sympathetic nerve blocks and determining the adequacy of sympathectomy, both of which are common in treating neurological disorders.[9] Carpal Tunnel Syndrome, recognized as an inflammation of the myelin sheath surrounding nerves in the hands, can be reliably diagnosed with Absolute Temperature Thermography.[10]

Diabetics can benefit from thermography, because they frequently suffer ulceration and extensive tissue damage in their feet because they have little nerve sensory feedback and grind the extremities. Neurological thermography can find which nerves are impaired and

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[6] Y.S. Kim and Y.E. Cho, "Pre-and Postoperative Digital Infrared Thermographic Imaging on the Lumbar Disc Herniations" Presented at the International Congress of Thermology (August 1992) and D.L. Newman et. al., "Low Back Pain: Clarification of MRI Findings with Thermography," Annual Meeting of the American Academy of Thermology (May 1989).

[7] A.A. Fischer, "Thermography in Differential Diagnosis and Documentation of Painful Conditions," Curr Ther Physiatr Phys Med Rehabil (1984) pp.131-145.

[8] J. Hubbard, J. Maultsby and C.E. Wezler "Lumbar and Cervical Thermography for Nerve Fiber Impingement: A Critical Review," Clin J Pain (1986:2) pp. 131-137.

[9] A.P. Pavot, D. Ignacio, and G. Gargour, "The Use of Thermography in the Diagnosis and Management of Reflex Sympathetic Dystrophy" (August 1992).

[10] Sheng Tchou, and Julia F. Costich, "Thermographic Study of Acute Unilateral Carpal Tunnel Syndromes," Thermology 1991: 3 pp. 249-252.

quantitatively measure how well medications are working. Ulcers on the feet also heal much faster in the presence of warm, well-perfused tissue near the damaged area, and thermography can readily assess this and offer a prognosis.[11]

As an adjunct to neurological applications, some researchers explained that applications in **sleep medicine** are possible within the mid-term. For instance, extracranial facial temperature and blood flow can be leading indicators of narcolepsy (an uncontrollable need for sudden, deep sleep), excessive daytime sleepiness, and sleep apnea.[12] In the cases of narcolepsy and excessive daytime sleepiness, a carbon-dioxide rich air (5 percent) is inhaled for three minutes to induce vasodilator stress, and the face is then thermographed.

3. **Sympathetically maintained pain**, which is chronic pain caused by constant firing of involuntary nerves and ganglia, can be displayed dramatically by thermography. A thermogram can "view" pain, which manifests itself in hotter areas surrounding the irritated nerves, and hotter superficial skin temperatures in the tissues controlled by that nerve bundle. In fact, thermography has found a strong following in the US among workers'-compensation lawyers seeking to show proof of their plaintiff's lingering pain from accidents, because no other technique can adequately image pain. A number of methods have been developed to assess sympathetic nerve functions, such as electrical skin resistance tests, calorimetry, plethysmography and thermocouple studies, but thermography allows large surface areas to be examined with minimal inconvenience to the patients, and provides real time, objective quantitative data. By contrast with the newer techniques, plain roentgenograms, myelograms, computerized tomographs, and, most recently, MRI, solely depict structural anatomical abnormalities that do not necessarily coincide with, and are not always responsible for, a patient's complaints.

Thermography has been very useful in diagnosing and pinpointing, for example, migraine headaches; in fact, Inframetrics, Inc. uses images obtained from migraine studies in its promotional literature. Thermography has been successful in pinpointing back pain, and lumbar pain in particular, due to the excess heat and abnormal neurological function in those areas. In diagnoses of chronic back pain, a gradient of 1°C from one side with the other is considered

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[11] R.P. Clark, et. al., "Thermography and Pedobarography in the Assessment of Tissue Damage in Neuropeathic and Atherosclerotic Feet," Thermology (1988:3) pp. 15-20.

[12] S. Govindan "Thermography in Excessive Daytime Sleepiness" Thermology (1989:3) p.140, and S. Govindan, "Thermography in Narcolepsy, Thermology (1988:3) pp.80-81 and S. Govindan "Thermography in Sleep Apnea" Sleep Research (1990:19) p.231

clinically significant.[13] As well, patients recovering from neurological injuries will very likely show asymmetrical heat distribution between the affected sides, so progress can be followed. The earlier the diagnosis of a sympathetic neurological disorder, the sooner one can avert more serious symptoms of "reflex sympathetic dystrophy," such as osteoporosis and trophic (sensitivity) skin changes. Infrared thermography is the fastest, most accurate system for those diagnoses, according to the interviewed.

4. The diagnosis of **arthritis and rheumatism**, of the knee, wrist, ankle, elbow, and metacarpus (bones of the hand) is one of the leading applications of biomedical IR imagers.[14] The case studies from clinical research suggest that widespread use of thermography for diagnosing arthritis can be expected within 3-5 years. Joints usually have a localized cool pattern, but are inflamed if there is arthritis. The surrounding membranes become very vascular and thickened. This can be spotted easily by thermograms showing the heat distribution in the region. Thermography can also be used to monitor whether the area is responding to anti-inflammatory medication, viewing the same area every few minutes. Depending on the shape, size, and gradient of the hot spots around and in the joint, specific diseases can be diagnosed, including chronic arthritis, osteoarthritis, or septic arthritis, for example. Other forms of inflammation-- from tennis elbow to sore knees -- can be pinpointed and monitored for improvement as the patient undergoes treatment.

5. **Tissue viability**, which is a function of circulation, can also be monitored very easily with IR thermography. Skin grafts used in either cosmetic surgery or remedial surgery can be monitored over several weeks to demonstrate that the tissue is alive and is being fed by the blood system. Thermal imaging of burns has proven very effective in evaluating the degree (first, second, or third) of damage to extensive burn victims, and has monitored those burns as they heal.[15] Ischemic (arterially blocked) limbs, especially after injury, can be monitored and, in the worst case, assessed by thermography to see where exactly a limb is dead in order to decide

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[13] A thorough review of systems requirements for such systems for imaging the back, which most acknowledged to be one of the most demanding applications, is in Michael Anbar, et. al., "Manifestation of Neurological Abnormalities Through Frequency Analysis of Skin Temperature Regulation," Thermology 1991, 234-241.\

[14] See E.J. Engel, "Thermography in Rheumatology," In EFJ Ring, B Phillips, eds., Recent Advances in Medical Thermology, (Plenum Press: 1984) pp. 425-437.

[15] R.P. Cole, et. al., "Thermographic Assessment of Burns Using a Nonpermeable Membrane as Wound Covering" Burns (1991:17) pp.117-122 and R.P. Cole, S.G. Jones and P.G. Shakespeare, Thermographic Assessment of Hand Burns," Burns (1990: 16) pp. 60-63..

where to amputate.[16]

6. **Oncological** diagnostic thermography calls for a combination of quantitative ATT, and dynamic thermography in its study of tumors. Since tumors are areas of abnormal, faster metabolic activity, the theory holds that the surrounding skin and tissues will be correspondingly warmer by at least a few tenths of a degree, and that there will be increased vascularity in the region. Hot cancers can register about 3°C warmer than the surrounding tissue, but cold cancers also exist which can be up to 1 or 2°C colder. Although extensive research in the use of thermography for mammography has been conducted since about 1968, this application is probably a long-term prospect as it requires major breakthroughs. Our sources agree that little will be concluded for seven to ten years.[17]

It is the radiology community's fear that annual exposure to low-level x-ray may be hazardous to women's health that has spurred interest in thermography. Thermography is especially useful in early detection of breast cancer, and well suited to being a pre-screening technique in conjunction with x-rays.[18] However, the application is far from mature, and may indeed be the last, and potentially most profitable, one to develop. Although interviewees stressed that quantitative, absolute temperature thermography is a vast improvement over the older systems, the clinical studies approach only about 85-90 percent accuracy in detecting cancers, missing many "cold cancers," and throwing many false positives, and several more years of research are needed. One use in mammography, supported by those interviewed, follows patients over several years and compares their successive thermal profiles. Another corroborative use alongside radiology is analyzing the prognosis for those who have already proved to have

[16] See A. Pogrel et. al., "Thermography in Assessment of the Vascularity of Soft-Tissue Flaps," Thermology (1990:3) 187-190, and A. Dittmar et. al. "Measurement by Heat Clearance of Skin Blood Flow of Healthy, Burned, and Grafted Skin," Prog Clin Biol Res (1982, 107) 413-420.

[17] See Y. Ohashi, et. al. "Significance of Dynamic Thermography in the Diagnosis of Breast Cancer" International Congress of Thermography (August 1992), and R. Amalric, et. al., "Prognostic use of Thermography in Breast Cancer" International Congress of Thermology (August 1992).

[18] G.C. Montruccoli, "Detection of in situ and early breast carcinoma by means of Angiothermographic Patterns" International Congress of Thermology (August 1992).

cancer.[19] The ability to detect the exact temperature gradient of the tumor has correlated well with necessary medication and the predicted mortality rate.[20] A major breakthrough has been the simultaneous use of a system using several wavelengths in IR mammography to overcome emissivity complications, and indeed such a machine is being used in clinical trials at the Sloan-Kettering Medical Center in New York.[21] However, the medical community will be circumspect about using IR for oncological diagnoses because of its failure in the 1970s.

Thermography can also assist in **hyperthermia**, which is a treatment for cancer where the temperature of a tumor is raised to about 43 to 45°C for about 30 minutes, in an attempt to kill a cancerous tumor. The surrounding area is maintained at a stable 40°C. Although this looks simple in principle, according to researchers, clinical practice often turns out to be more complex because the body constantly tries to either diffuse or cool the heat in the tumor receiving the microwave or radiowave treatment. As a monitoring tool, IR thermography would be dynamically applied in a "process control" loop which would constantly regulate the heating to maintain the steady gradient between unaffected and 45°C areas.[22] This application a possible within the next five to seven years, due to the complex software considerations and further clinical study.

7. **Neonatology**, which focuses on an infant's physiological growth during the first few

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[19] E.E. Sterns and B. Zee, "Thermography as a Predictor of Prognosis in Cancer of the Breast," Cancer (1991:65) pp. 2676-80.

[20] H.U. Ulmer, M. Brinkmann and H.J. Frischbier, "Thermography in the Follow-up of Breast Cancer Patients After Breast Conserving Treatment by Tumorectomy and Radiation Therapy" Cancer (1990:65) pp. 2676-80

[21] See, for instance, S. Hejazi, D. Wobschall, R. Spangler and M. Anbar, "Scope and Limitations of Thermal Imaging Using Multi-wavelength Infrared Detection" Optical Engineering (November 1992) pp. 2383-2393

[22] J.H. Torres, T.S. Springer, A.J. Welch and J.A. Pearce, "Limitations of a Thermal Camera in Measuring Surface Temperature of Laser-irradiated Tissues" Lasers Surg Med (1990:10) pp. 510-23.

months of birth, would duplicate the applications mentioned above.[23] IR thermography can help in the diagnosis of hyper-endocrine conditions such as hyperthyroidia (because the thyroid gland lies close to the skin), as well as juvenile arthritis, and myriad vasomuscular and neurological disorders before symptoms are fully developed and before the babies can express their pain.[24] Uses under present study, for future application, are measurement of skin blood flow in low birth weight infants, and in atopic children to study dysregulation of cutaneous vasomotility (unstable skin temperature).[25] Another application in neurodiagnostic examination is to verify the symmetry between halves of a baby's body to screen for nerve injuries, which most often manifest themselves in asymmetrical nerve stimulation.[26] Neonatal applications, from the systems design standpoint, would require special reflective arrangements to obtain a thermal image of the child inside the incubator, and would rely on dynamic thermography to study temperature transformations during the baby's growth.

8. By contrast, **dermatological thermography** will rely on Absolute Temperature Thermography because certain dermatological disorders, as well as burns, are likely to affect skin emissivity, and can be diagnosed with a "snapshot" of the area. As in other applications, testing over several wavelengths can sort the emissivity from the absolute temperature. For example, subjects we interviewed highlighted thermography for the study of cutaneous metastatic melanoma (a form of skin cancer which is very prone to spread to other organs), and malignant melanoma.[27] Thermography can be used to test for allergies to cosmetics, chemicals, or

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[23] A good overview is in J.K. Stothers, "The Special Thermal Physiology of Newborn Infants," in EFJ Ring and B. Philips, eds. Recent Advances in Medical Thermology, (Plenum Press:NY) 1984; pp. 17-25.

[24] J. Czigany, "Infrared Thermography of the Head and Neck in Children," Thermology (1986:2), p.70.

[25] F. Ippolito, A. Di Carlo and G. Leone "Infrared Thermography in Atopic Children: Dysregulation of Cutaneous Vasomotility" International Congress of Thermology (August 1992) and L. Hanssler and C. Roll "Neonatal Infrared Telethermography and Laser Doppler Flowmetry: Measurement of Skin Blood Flow in Low Birth Weight Infants." International Congress of Thermography (August 1992)

[26]. D, Ignaccio, et. al., "Neonatal Thermography," Meeting of American Academy of Thermology (August 1989).

[27] M. Cristofolini, et. al. "Value of Thermorgaphy in the Diagnosis of Malignant Melanomas of the Skin," in EFJ Ring and B Phillips, eds. Recent Advances in Medical Thermology (Plenum Press: New York) pp. 631-635.

antigens, because the epidermal veins dilate when irritated. Systems will need to be designed with a short focal length to accommodate examination close-up.

9. **Ophthalmology** (the study of diseases of the eye) will also require measurement of absolute temperature and a short focal length.[28] The temperature of the cornea has long interested ophthalmologists, since the eye loses heat through the cornea, and the temperature of the cornea is a function of the internal temperature of the eye. Also, local processes involving the cornea may manifest themselves as changes in local temperature. The use of thermography in ophthalmology is still immature, however, according to those surveyed, because precise instrumentation was never made available.[29] According to people we contacted, resolution of <.2mm on the image of the cornea would be needed, with a thermal resolution of <0.1°C, and there needs to be a precise correlation between thermal profiles and anatomy. The only present method is contact measurement of the cornea, which is not the preferred method because of the discomfort experienced by the patient. This application is estimated by clinical users to be available in three to five years.

Lastly, biomedical IR imagers may have great promise during **surgery**. The earliest application has been in assessing perfusion (the pumping of fluid through an organ to keep it alive) during open heart surgery[30]. The detector would be looped into a process-control feedback system which would regulate and optimize the heart's temperature. With such a system, there is potential for use in most transplantations and anastomosis (separation of two

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[28] J.C. Monotoro, et. al. "Use of Digital Infrared Imaging to Objectively Assess Thermal Abnormalities in the Human Eye," Thermology (1991:3) 242-248, and R.F. Haverly et. al. "Digital Infrared Imaging of the Human Cornea and Sclera," Archives of Ophthalmology (1991:1) 25-33.

[29] A review article, which discusses system design, is J.C. Montoro, et. al., "Use of Digital Infrared Imaging to Objectively Assess Thermal Abnormalities in the Human Eye," Thermology (1991:3) pp. 242-248.

[30] H. Adachi et. al., "Real-Time Infrared Imaging for Perfusion Assessment in Heart Surgery: An Experimental Model," Thermology (1986:1) pp. 7-12, and F.W. Mohr et. al., "Thermal Coronary Angiography: A Method For Assessing Graft Patencyh and Coronary Anatomy in Coronary Bypass Surgery," Ann Thorac Surg (1989:47) pp. 441-449.

abnormally joined tissues) procedures. This would require real-time (>30 frames/sec) imaging, and a wide temperature range (5° to 40°C) for the monitored organs. Secondary, absolute temperature images are also desirable as backup. Because of the operating room environment, these systems would need to be double-insulated electrically and coupled with the controlling computer through fiber-optics. Due to the complexity of such an application, efforts are not likely to bear fruit for about five to seven years, according to those interviewed.

Detector and System Design. There was widespread agreement among the interviewed researchers and clinical users on the specific design needs of IR thermography systems. For most of the possible applications, a 512 X 512 staring array offers both state-of-the-art capabilities and the ideal resolution level. Real-time updating is necessary for many of the applications in neurology, sympathetic pain analysis, and surgery. All applications would benefit from rapid updating of the image because the clinician needs to focus, zoom, and change angles and optical filters to attain the best image, and would be delayed by slow systems.

Whereas the military community seeks infrared detectors with great *uniformity in detector materials and pixels*, the medical establishment is more concerned with *stability* and consistent performance over long operating periods. Variance and sensitivity are desirable in thermographic imaging systems only if they can be measured under identical calibrations over a period of several months, since many of the systems will be used to monitor patients' recovery or degeneration over time.

The minimum temperature variation which an IR biomedical detector would need to cover is about 2°C, and most systems would need to distinguish on the level of 0.01°C at a speed of 60 frames/second. Systems which now exist can distinguish down to about 0.1°C, but update very slowly because their scanning mechanism needs to spend a longer integration time on each pixel to gain that sensitivity. However, there is some uncertainty about these requirements, and some leeway depending on the application. Some researchers believe that thermography systems could succeed with as little sensitivity as 0.1° C, and response times as long as one second. By contrast, the diagnosis of neurological dysfunction is perhaps the most demanding application. It could potentially require a very hard-to-achieve precision of about 0.001°C, a linearity less than 0.000001°C/1°C, a long term linear drift less than 0.01°C/hour, a response time of 0.001 seconds and a spatial resolution of 1mm.[31]

The systems which exist today are cumbersome and better suited to research than clinical

[31] M. Anbar, "Recent Technological Developments in Thermology and Their Impact on Clinical Applications," Unpublished, 1992.

use. Most existing biomedical IR systems require liquid nitrogen to be poured into the cryogenics, and need topping-out during operation. This is a barrier to making the technology accessible to the medical community. Thermo-electric coolers would be greatly preferred, especially because they could operate off lower and commonly available voltages. But since biomedical thermography systems will probably not need to be lightweight or portable, closed-cycle Joule-Thompson cryocoolers could be satisfactory.

Biomedical systems also require extensive environmental control, including a draft-free environment, tight humidity controls (55± 10 percent), and air thermostated to within 0.1°C. These requirements, of course, will add to the cost to end-users.

An often repeated concern of end-users and trade association members was the need for greater interaction between medical end-users and system designers. A lack of such interaction is said to have caused the initial failure of infrared thermography in the US, because systems were never able to reach their potential, and users did not understand their limitations. Such communications may be particularly crucial, as many clinical users claim that thermography systems should be designed to meet the needs of the specific intended field of use, neurological, vascular, oncological, etc.

Japan's IR Thermography Program. Medical communities in some foreign nations have been very interested in thermography. In Europe, thermography was first used to observe metabolic abnormalities and heat convection phenomena, which included applications for diagnosis and treatment of rheumatoid arthritis and varicose veins. Then the technology spread to neurologists, who use it to image temperature-control abnormalities.

It is in Japan, however, where widespread clinical interest in thermography has established a litmus test for the technology's potential. The Japanese have clinical studies underway in about 500 hospitals, which is over 20 percent of all hospitals in Japan. The effort is led by a consortium of Japanese infrared imaging corporations, particularly Fujitsu, which has provided various MCT- and InSb- based thermographic machines. Funding is substantial, nearing perhaps $10 million since the beginning of the 1990s, with a large portion of the funding in the form of free equipment and, most importantly, on-going technical collaboration with end-users. The funding is channelled through the University of Tokyo's Research Center for Advanced Science and Technology, which oversees the clinical studies.

Infrared thermography gained approval for clinical use by the Ministry of Health Care in 1981. Unlike the case in the US, the Japan National Health Care Insurance Scheme covers thermography testing. There are no restrictions for clinical applications, with modest insurance-covered allowances for one general test and one stress test per diagnosis. The Japanese Industrial Standard sets guidelines for thermographic testing, standardization of thermographic images, and sets standards for basic thermographic image handling. The five standard clinical uses of thermography in Japan are for peripheral vascular diseases, neuromuscular diseases, breast tumors, dermatology and oriental medicine. Most importantly, the Japanese clinics employ IR thermography as part of a diagnosis decision tree -- trying it as either a first-step, inexpensive diagnostic tool or, later, in prognoses to evaluate a disease once it has been confirmed by other means.

The systems now in clinical use are predominantly single point scanning devices, with a few SPRITE style systems. Japanese researchers have been waiting to receive mosaic arrays, which they recognize will offer better resolution and will simplify the optics and mechanical upkeep of their machines. Several researchers we contacted had seen AGEMA IR imaging systems in the Japanese research labs which reportedly had been purchased by Fujitsu

In all, six IR imaging instruments have been approved by the Japanese government. Three are MCT-based scanning arrays, and comprise the vast numerical majority of units in clinical use. They are the Fujitsu-Nihonkohden "Infraeye 180," the JEOL "Thermoviewer JTG4130," and the NEC-Sanei "Thermotracer 6T67," all of which use MCT cryogenically cooled to liquid nitrogen temperature. Two other approved systems are the AGEMA thermo-electrically cooled "Thermovision 870" SPRITE system and the Hughes (USA)-Japan Avionics "Thermal Video System TVS-2000ME," which is a ten element scanning InSb array which uses Joule-Thomson effect cooling. A distant sixth machine is the "Telmamma" contact thermography unit by International Products and Services which is produced in Italy.

Two additional systems are now being reviewed by the Japanese government: the Rank-Taylor-Hobson "Thermal Camera," which is a SPRITE 8 element scanner using Joule-Thomson effect cooling, and the Mitsubishi Electric "Thermal Imager CCD," which is a 512 X 512 mosaic model. For all these systems, prices range from about $45,000 for Mitsubishi's 512x512 CCD system, to $65,000 for complete InSb-based systems, including the software, the detector suite, and imaging screens.

Market Analysis. In this section we discuss the potential market for biomedical thermographic machines. Based on the relatively negative perception of thermography within the medical community, we project that the technique will remain a *corroborative*, rather than a primary diagnostic technique through the mid-term. Based on this assumption, we discuss the potential time-to-market for various applications, and project sales and unit costs through the end of the 1990s. We then discuss the special niche for MCT-based detectors in the emerging biomedical market.

Current Perceptions of Thermography. The major hurdle which confronts thermography is that the medical community perceives it to be an immature technology which promises a great deal but delivers little. This view stems from the experience in the mid-1970s, when the biomedical community was searching for an effective technique for early breast cancer detection. Infrared thermography was touted as the answer, but was soon eclipsed by radiology, because thermographic technology was very immature at the time, with very low speeds (up to 2 minutes to generate a single image), poor resolution, and poor fill factor. The two techniques which were then in use, and eventually undermined the medical community's confidence in thermography, were based on contact thermography and transillumination. In contact thermography, developed in the 1960s, a clinician stretched a sheet of temperature-sensitive liquid crystal over the area to be imaged on a patient. As discussed further in the section on suppliers, contact thermography updates the IR image only very slowly, is only minimally reliable, and is much too subjective. In the other technique of "transillumination," infrared heat was shined on a breast and the infrared profile or shadow was viewed by a clinician. This was neither quantitative nor reliable because absolute temperature readings are obscured by uneven emissivity across the skin's surface, and requires simultaneous imaging in several wavelengths to offer an accurate temperature reading. In short, neither thermographic system fulfilled the promise to replace x-ray mammography, and the failure of these early systems created an early, negative image of IR technology in the medical community.

Neuromuscular applications were the second area to be considered for thermography, and the technique seemed to have garnered a measure of support in 1987 when the long-awaited American Medical Association's Council on Scientific Affairs report, "Thermography in Neurological and Muscoskeletal Conditions" gave positive approval of thermography.[32] The American Academy of Thermology in conjunction with the International College of Thermology had been lobbying for years to gain approval for their technology. Approval from the medical societies is a crucial step in convincing the US health care industry to cover the costs of thermography tests. Earlier that year, the American Academy of Thermology an international bibliography containing over 4,900 published medical articles on thermography[33].

However, the tide turned again against health coverage for thermography when a 1989 report from the Office of Health Technology Assessment (OHTA) of the US Department of Health and Human Services gave only a luke-warm review of the technique, and several medical societies subsequently followed suit, including the American Society of Neurologists, which rescinded its previous approval of thermography. That OHTA report concluded that, "most investigators recommend thermography only as a screening tool, as an adjunctive diagnostic

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[32] See AMA Council on Scientific Affairs Report, "Thermography in Neurological and Musculoskeletal Conditions," Thermology (1987:2) 600-607.

[33] M. Abernathy and T. B. Abernathy, "International Bibliography of Medical Thermology" (American Academy of Thermology: Washington, DC) 1987.

device, and not as a primary diagnostic guide."[34]

Many of thermography's proponents found the study's conclusions very surprising, because, as one said, "most of the OHTA report contains impressive evidence of thermography's usefulness in a variety of conditions. Many favorable articles, along with some critical studies, were fairly discussed in the report's body. In view of this, the highly critical conclusions at its end come as a surprise. It is difficult to understand how the same author could arrive at conclusions in the summary that often contradict the body of the report."[35]

The consensus of the thermographers we interviewed was that thermography is ideally a corroborative and secondary diagnostic tool, but that this is not a negative drawback, as some would make it out to be. One proponent of thermography said that there was a "failure to appreciate that thermography does not compete with or is not outperformed by the new imaging modalities, such as CT or MRI. Educational efforts should emphasize that thermography offers a unique physiologic reflection of pathology that may confirm or enhance the anatomic findings of other diagnostic imaging modalities or render them more or less clinically significant[36]."

To clarify these mixed reviews given to thermography, the AMA is re-evaluating thermography, and has appointed a committee of physicians to conduct a study, but little has been done despite a December 1992 deadline for their report. In the meantime, the Health Care Financing Administration, which oversees Medicare, decided just in December of 1992 to no longer cover diagnoses using thermography. Most national health insurance firms still support thermography, but disavowal by the HCFA is a major setback, and realization of thermography's potential market will be limited until this decision is reversed.

<u>Market Potential</u>. The consensus among those surveyed and the literature was that, at least in the mid-term, IR thermography will be used as a *complementary* and integral diagnostic tool alongside systems which image structure. The consensus was that biomedical images of both structure (by X-rays, MRIs, or CAT scans) and function (by thermography) will contribute to an effective diagnosis, because they each offer distinct, corroborative data. For example, a team at Johns Hopkins University recently combined radiology and thermography to diagnose pain in a

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[34] H. Handelsman "Thermography for Indications Other than Breast Lesions" No. 2. Office of Health Technology Assessment, US Department of Health and Human Services, 1989.

[35] R. Pochaczevsky, "The Value of Thermography as a Critical Diagnostic Test: A Review of and Response to the 1989 Office of Health Technology Assessment Report of Thermography for Indications Other Than Breast Lesions" <u>Thermology</u> (1991:3) pp. 227-233.

[36] Pochaczevsky, ob. cit.

patient following total knee replacement. The X-rays found that the knee prosthesis was satisfactorily aligned, with the bone and metal intact. Moderate swelling was detected in the tissue surrounding the knee. The thermogram, however, revealed significant thermal asymmetry; the knee affected was 2.4°C warmer than the lateral knee. Hypesthesia, a state of vascular atrophy, was found which matched well with the area of numbness in the patient. Based on the x-ray alone, "reflex sympathetic dystrophy" (RSD) would have been diagnosed and doctors would have prescribed sympathetic nerve block or sympathectomy (ie. surgery which interrupts the troubling nerves). However, the researchers found no sign of RSD using a thermogram, and prescribed instead a much milder and more effective system of physical therapy, with success.[37]

If thermography can overcome the negative perception of its diagnostic value, a substantial market is on the horizon. Neurology, vascularity, sympathetic pain disorders, tissue viability and arthritis/rheumatism will be the primary applications in the mid-term. Potential applications will require high-end capabilities, integrating state-of-the-art imaging sensitivity and stability. These early thermographic systems should cost between $40,000 and $100,000, with an average price around $50,000. Sales could reach up to 6,000 or 7,000 thermographic machines a year, at about $300 million a year within the next ten years. Half of those units could be for neuromuscular applications alone, because that area has been the most extensively researched.

A second wave of sales could occur after 1997 for oncology and breast cancer research, offering a second market for high-end thermographic systems, at similar prices. Ancillary applications in neonatology, ophthalmology, and dermatology also will develop after 1997. According to our interviews, these applications will benefit from the development of thermographic technology rather than lead it. Surgical applications of thermography will not be in side use until well in to the next decade because of the complexity of the software and the extensive clinical studies which would have to be completed beforehand.

By comparison with other biomedical diagnostic equipment, thermography's market potential falls between that of ultrasound and electro-cardiograms (EKGs). Ultrasonic diagnostic machines image structures only a few inches beneath the skin and sell for between $150,000 and $200,000 each. There are roughly 35,000 ultrasonic biomedical machines in operation in the United States, and another 35,000 worldwide. Ultrasound's similarity to thermography is even close, in that the AMA initially disapproved of ultrasound, just as it has thermography. It took roughly 25 years for ultrasonic technology to be accepted by the AMA's official bodies. Ultrasonic machines gained widespread acceptance only after software was developed to

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[37] M. Trattner, et. al., "Pain Following Total Knee Replacement," Thermology (1986:2) pp.45-46

manipulate the data in a way that accommodated the medical users' needs. The AMA's initial disapproval receded five years after a concerted effort by industry to develop systems which filled the needs of clinical users. Several proponents told us that thermography was within five years of breakthroughs in software and systems design that would allow thermography to be more widely accepted by the medical community. The challenge for thermography is not to find new applications. They are well known. The challenge is instead to persuade medical users to try the machines despite the community's previous lukewarm review.

The potential market for infrared thermography also tracks that of EKGs, another diagnostic technique. Both techniques are non-invasive and are therefore relatively inexpensive because overhead costs, such as government certification or safety inspection, as with x-ray machines, are not necessary. Users of both EKGs and thermography do not need to be nearly as extensively trained as are radiologists. Most cardiologists and internal medicine practices have EKGs, with about 400,000 units worldwide. EKGs have been picked up by the medical community much faster than MRIs or CAT scans because of their very low cost, at about $20,000. Like thermography machines, EKGs also display data immediately, instead of taking long computation times as MRIs and CAT scans do. Although it is unlikely that thermographic systems will sell as quickly as EKGs, it offers similar advantages in cost and technological advancement which make it attractive to the medical community.

As compared to EKGs which are useful in any internal medicine practice, the specialized character of thermographic applications will restrict their market to hospitals, clinics, and specialized group practices, such as neurology, pain management, and sports medicine. Each of these centers might purchase several advanced IR machines and design a controlled environment around them, as has been done with CAT scans, ultrasound, and MRI systems. One firm we contacted produces environmental control rooms to accompany their MCT-based detectors. The rooms cost as much as their $45,000 thermographic machines.

MCT-based arrays are well placed to capture a significant portion of the evolving infrared thermography market. The trend in Absolute Temperature Thermography towards multiple wavelength readings benefits MCT arrays, which are the only systems able to cover all relevant wavelengths. InSb-based machines can not image in all the wavelengths proposed for multi-wavelength studies (about 2-14 microns). Moreover, the vast majority of applications described in the literature will need to view upwards of a 10 degrees celsius deviation in human body temperature, which requires a broad wavelength band of view. A minimum desired range is from 2-6 microns in the MWIR or 10-14 microns in the LWIR. MCT-based arrays will uniquely enable systems to both determine temperature readings in each pixel of a picture, and offer real-time screening at 512 X 512 line high resolution. Most applications are ideally suited to MCT's imaging strengths: high sensitivity, a wide wavelength view from about 2-14 microns, and the ability to image in real time.

One hurdle which MCT-based thermographic systems may encounter is the lack of a widespread consensus about which wavelengths offer better thermography images. The debate is between advocates of the 2-6 micron and 10-14 micron ranges. It is plain that in an ambient temperature of 22°C, an unclothed healthy person might have a skin temperature that ranges from 35°C over the sternum to 25°C over the feet; at these temperatures, peak infrared emission occurs around a wavelength of 10 microns. But both infrared windows appear to image effectively. The more important factors in design of the system are sensitivity, performance, resolution, and reliability. In the 2-6 micron window, InSb is competitive with MCT-based systems, but InSb may prevail, according to manufacturers, because it is less expensive and offers satisfactory resolution. In the longer wavelength window, however, MCT is the only choice since InSb does not extend into the 10-14 micron range. The LWIR offers the better resolution, but it is counterbalanced by its higher expense. At a price, MCT offers the hard-to-achieve detector sensitivities which are crucial to several of the potential fields of application for thermography: neurology, sympathetic pain studies, oncology, surgery, and many of the vascular applications.

The broad consensus we found was that MCT will be the workhorse of the thermography field, and will dominate the eventual market. PtSi-based detectors would be an inexpensive alternative and could offer very large mosaic arrays at affordable cost, but would have poor quantum efficiency and poor fill factor. InSb arrays, on the other hand, would also be inexpensive, but could not offer the sensitivity, absolute temperature measurements, and multi-wavelength and LWIR potential that MCT has. The one formidable barrier to widespread use of MCT-based IR arrays will be its cost.

Japanese infrared system manufacturers will have a leg up on the international biomedical market, if IR manufacturers in the US and Europe do not design systems now which will be ready within about five years. Despite the myriad studies and many proponents of IR thermography in the US, commercial IR detector companies have taken a "wait and see" attitude. Many U.S. thermographers argued that Absolute Temperature Thermography could benefit immensely from MCT arrays, especially larger, 256 X 256 staring systems, but told us that hardly any systems had been loaned or sold to them by industry. The infrared imaging companies have appeared content to pass over biomedical applications, despite evidence of a sizable potential high-end market.

Suppliers. Seven firms supply most of the infrared thermography market in the US. They each manufacture infrared imaging systems for a wide range of applications, including medical uses. Each of these firms relies on other segments of the infrared detector market for most of their earnings, most notably the market for industrial IR detectors. The machines listed below are referenced in later application sections, where they are also used. The firms adapt existing systems for biomedical applications by creating software which meets the medical community's needs. Most of the existing biomedical thermography systems share a single detector scanning model with about 200 X 200 line resolution, an average price of $40,000, and IBM-based software which make the thermography machines usable for biomedical applications. There are three physical components in all these thermographic systems: an IR detector module mounted on a tripod, a color monitor which presents an image in about 16 distinct colors plus gray scale, and a PC-based computer to analyze data.

• **Hughes Aircraft** entered the thermography market at the start of the 1980s, and exited shortly after the unfavorable AMA report. Hughes had provided a "Protoeye Model 3300" which was MCT-based and cryocooled to liquid nitrogen temperature. It was as sensitive as.1°C, and had a 200 X 200 line resolution. The Hughes IR system used a single scanning pixel, with extensive scanning optics. This was a moderately priced unit, at $40,000. It imaged in real-time, and had an isotherm capability which could, for example, compare the heat profile of both hands, or of both sides of the back. Although Hughes claims the market turned unprofitable after the AMA's negative report on thermography, outsiders maintain that Hughes simply decided to focus on the burgeoning military IR sensor business.

• Swedish-based **AGEMA Infrared Systems** provides the thermo-electrically cooled "Thermovision 900" series, based on SPRITE detector array technology. Its screen images at 20 times/second, and offers, by comparison with other systems on the market, low sensitivity because it is InSb-based rather than MCT-based. It has a slower quantum efficiency typical of InSb, and is not very sensitive at higher imaging speeds because a scanner can only spend a fraction of a second on any given pixel. This is in fact typical of almost all the systems on the market. AGEMA's system is the most expensive in widespread production, at $90,000 to $100,000. The system is reportedly the leading InSb MWIR unit on the market, although AGEMA has debated internally whether it is profitable to stay in the thermography system business.

• **Inframetrics** in North Billerica, Massachusetts, has developed several generations of biomedical thermography systems, ranging from its older Model 500 series during the early 1980s to its current Model 700 and Model 800 series. It is a real-time, video rate (60 updates/ second), MCT-based imaging system using a single scanning detector. The prices for Inframetric's systems range from about $30,000 to $50,000 depending on the sensitivity and speed at which the image updates. This system is cryogenically cooled with Stirling close cycle cooling.

• **FLIR Systems** in Portland, Oregon, was once a division of Hughes, and markets technology originally licensed from that corporation. FLIR Systems sells one high resolution MCT-based scanning system for the biomedical thermographic market. It purchased the technology for that MCT sensor from Hughes when it exited the market in the late 1980s. The principal weakness of that system is its software, which does not allow many statistical, zooming, and isotherm measurements, according to users we contacted. FLIR Systems is reportedly discussing new models with several of the leading commercial and military detector companies. They would be the system designer in joint ventures, utilizing detectors manufactured by other companies.

• **Dorex, Inc.** of Orange, California, is an innovative single-point MCT-based detector vendor which helps design environmentally stable rooms in which patients can rest for 20 to 30 minutes before a thermogram, in order to minimize the impact of external variables. The detectors, which use single-point scanning MCT-based technology, cost about $45,000. The accompanying examination room climate control equipment also costs $45,000. Although Dorex is marketing a MCT-based staring focal plane array in a closed-cycle cooler, which, according to others in the industry, it purchases from Rockwell, it decided not to field a biomedical thermographic model, because it claimed the $75,000 price would be too expensive.

• A minor player is **Bales Scientific** in Walnut Creek, California, which purchases MCT-based single-point scanning detectors, placing them into the "MCT 7000" which specializes in manipulating raw data in dynamic thermography applications. Bales' machines are more popular among research scientists needing high precision equipment for non-destructive evaluation.

• Two minor participants are the contact thermography companies. **Flexi-Therm** of Westbury, NY, a subsidiary of E-Z-EM, Incl, and **International Products and Services** in Milan, Italy, produce contact thermography systems which cost about $3,500. They measure temperature from about 20°-40°C at a .1° sensitivity. However, the screens update extremely slowly, and the only way to fashion a dynamic diagnosis is to videotape a contact thermography screen. Contact thermography systems were the predecessors to current scanning IR models, and use liquid crystal contact sheets which are placed firmly and uniformly against the surface being examined. A color photograph is taken of the iridescent colors produced by the effect of temperature on the light-scattering properties of the liquid crystals. These devices are neither solid-state nor digital. To diagnose a patient, a clinician subjectively views the temperature profile. The color sequence usually ranges from yellow-red for cool temperatures through green to blue for hotter colors. Officials we interviewed said unanimously that the contact thermography is too imprecise for most medical work, and its market share will continue to shrink.

## Non-Destructive Evaluation

Infrared detectors have been used to test materials non-destructively for the past twenty years in applications which range from the exotic to mundane. Non-destructive evaluation (NDE) offers a significant, albeit niche, market for sophisticated focal plane arrays. Moreover, the same technological trends already making systematic and quantitative assessments of thermal profiles which have revitalized predictive maintenance, biomedical imaging, and remote sensing applications, are causing a renaissance among engineers of sophisticated NDE equipment. We estimate that over two-thirds of the NDE thermography market could require state-of-the-art thermal imagers with the high sensitivities and extremely fast image rates that favor staring IRFPAs based on MCT. That high-end market could be worth $345 million annually within about five years.

Since there are three distinct families of applications for thermography in NDE, we discuss applications and system designs under the same heading. We then discuss the potential market for each of the three families of applications, and conclude with a section on suppliers. Appendix I lists the individuals we interviewed for this segment.

Applications. Non-destructive evaluation, also called non-destructive testing, is the examination of material after its production to detect flaws, cracks, delaminations, voids, etc. without altering or destroying any part of the test piece. Thermal NDE can be conducted on objects as simple as plywood, automotive paint, or fiberglass, or as complex as polymers, graphite-epoxy compositesm, or epoxy-glued aluminum lapjoints for airplane panels.

NDE can be defined by explaining *what it isn't*. NDE differs from process control in some applications because it examines products after-the-fact, without feedback into the manufacturing process which is the hallmark of process control. In still other applications, NDE examines aging materials to ensure that they have not atrophied. NDE differs from predictive maintenance because it examines passive, solid-state objects like insulation in homes, rooftops, or aging composite materials, rather than moving engines or high-voltage electrical equipment.

In general, we found three broad areas of applications for infrared imaging within NDE: (i) the inspection of IC boards, (ii) building and structure diagnostics, and (iii) quality assessment of sophisticated materials likes composites and laminates.

(i) Integrated Circuits. Virtually all leading electronics companies are experimenting with thermal imaging to varying degrees to detect anomalies in integrated circuits. As another tool available to engineers designing "total quality management" regimes, thermal testing can be conducted at any phase in production, from initial microelectronics design as an evaluation tool, to bare-printed circuit boards, to completely filled PC-boards, to repaired circuit cards. Thermal imagers can detect a variety of defects in electric circuit cards, including bad components, incorrect components, poorly soldered components, shorted circuits, incorrect current levels, excessive power dissipation, off-spec placement of components, inadequate signal- and ground-lead capacity, and inadequate cooling assemblies.

Two types of thermal imagers are generally used for inspection of integrated circuits. In one case, thermal microscopes are optimized for high resolution (600 X 500) over narrow fields of view (less than 0.5 meters). In the other, thermal microscopes are optimized for wide fields of view (greater than 0.5 meters) and moderate resolution (250 X 200). Temperature sensitivity of 0.1 °C is the norm. In both cases, infrared cameras from the major commercial producers have so far been adapted by electronics firms to view the integrated circuits.

All electrical circuits have a unique thermal profile which results from heat generated by electrical resistance as current passes through the circuit. Circuit defects change the flow of current and/or electrical resistance (and heat pattern) in affected parts of the circuit. To identify such defects, imagers used to compare the thermal signature of the unit under testing with that of a known good unit, under the same conditions. It was reasoned that virtually any defect in a bare card or PC-board will generate atypical temperatures of at least 0.1 °C. With high-voltage components, however, several companies explained that thermal anomalies of 0.1 °C were smaller than the overall standard deviation of thermal profiles from one chip to another. So engineers developed a more recent technique, "thermal ratio analysis," in which three thermal pictures are compared in quality checks: one of an accepted, normal board, another of the test board with a very low voltage applied, and another with the test chip under full power. Comparing the high-voltage thermal picture of the board with the accepted standard is used as a "quick-and-dirty" first test to confirm that the board is within broad tolerances. Subtracting the high-voltage image from the low-voltage thermal image, however, offers a more exact measurement of that board's thermal performance because it shows the change in temperature within the board itself, rather than comparing it with an absolute standard. If the *ratio* change exceeds certain tolerances, then the board is rejected.

Thermal imaging offers a rapid and contactless "go/ no-go" test on PC boards. In go/no-go quality checks, a thermal machine vision system would accept or reject a board or PC card depending on a comparison of its thermal profile with an accepted standard. Infrared imaging systems could eventually be inserted into an assembly line to examine PC-boards at several steps in production. The best point to do this is early in the manufacturing process, when the printed circuit boards are still bare of have minimal contacts. As circuit board traces become thinner, circuit layouts become denser, and boards incorporate more layers. Undiscovered problems lead to higher repair costs if they are not spotted early. Board costs soar, in particular, after components are installed.

IR thermography offers three advantages over traditional techniques for go/no-go testing. First, it eliminates contact probes, the traditional go/no-go test technique, which frequently causes damage to circuits. Second, thermography surveys all layers and all active signal and power traces simultaneously, which takes out the trial-and-error prevalent in IC board repair. Thermography performs five times faster than contact probing. Third, thermographic testing also eliminates the use of high current levels to cause slightly defective switches to malfunction, and which would show up in electrical tests. Several quality control engineers posited that the higher speeds of electronic components and more densely populated printed circuit boards will continue to make boards more difficult to probe electronically. Eventually these trends will force the adoption of thermal imaging by more electronics manufacturers.

Precise fault detection in IC boards and cards is a more complicated task because thermal anomalies in electronics often appear in components of a circuit affected by defects in addition to the real site of the defect. For this reason, users need a technical understanding of the circuit's dynamics to diagnose a fault. The traditional instruments for fault detection are oscilloscopes, logic analyzers, and bus emulators. But to use them effectively, an engineer needs to know where to look in advance. By acquiring a thermal profile of a PC board and then comparing that image with an accepted standard, IR thermography can diagnose faults quicker and more simply, and without the need to be an expert on each specific board.

Several military depots have adopted thermal imaging in the repair of printed circuit boards. They use imagers to perform preliminary gross fault diagnostics before testing the boards with probes. The Department of Defense, moreover, has developed software-driven, semi-automated systems, so relatively unskilled operators can perform the screening. Engineers at the Army's Anniston Depot, for example, often detect conditions that indicated a probable failure of a component. Conventional probe techniques cannot detect problems until the component fails.

Finally, thermal imagers can aid PC-board design by helping to evaluate prototypes. Although there are many design assessment tools for predicting circuit board temperature, many components, such as ASICs, are without specific thermal models. Also, board designers striving to reduce real estate (space on PC-boards) and increase capability have frequently set up unpredictable thermal interactions between circuits and components without modeling them first. Thermal imagers could be invaluable in thermal analysis of prototypes to quickly identify and eliminate heat stress problems before sending designs to the production floor.

Electronics firms are now seeking to integrate thermal imagers into IC board design, production, and design evaluation processes. According to the product manager for UTI in Milpitas, California, for example, some users of thermal imagers are saving up to $150,000 per week by identifying and fixing defective boards they would otherwise scrap as taking too long to diagnose. An executive at Honeywell said they save less money than UTI, but that their thermal imaging system paid for itself within two years. Tektronix, in Wilsonville, Oregon, has used thermal imaging studies to improve its thermal modeling software to the point where its predictions almost exactly match the actual thermal profile. Tektronix's ultimate goal is to skip real-time thermal imaging and rely completely on modeling for its electrical components. Companies like Compaq are also routinely using thermal imaging to analyze the thermal changes when substituting IC components from one vendor to another, or from one architecture to another.

As design evaluations tools and as fault-location tools, IR thermography's future already seems assured. In producion line applications, however, current thermal imagers are too slow and inconsistent to gain widespread acceptance. On high-speed assembly lines, thermal analysis now takes 45 to 60 seconds, according to consultants we contacted. Imagers would need to complete a test in 15 to 20 seconds to keep pace with the speed of IC assembly lines. Achieving consistency is also more difficult in high speed IC manufacturing processes, because many extraneous factors complicate imaging. Such factors as shifting ambient light, fixtures and shadows, and power fluctuations complicate imaging. Also, many components are installed on PC boards a few tenths of an inch off spec; such minor deviations do not affect the board's functioning, but can change its thermal profile. This can set off false warnings of faults in the board. Moreover, quality control engineers are wedded to older inspection techniques, such as contact-probe testing, and are hesitant about adopting newer techniques. Until these problems are overcome, in about two years by our estimates, thermal imagers will only begin to scratch the surface of applications among electronics producers.

(ii) Building and Structure Diagnostics. IR detectors are used in four specific types of applications under the heading of building and structure diagnostics: to assess roof moisture and damage, to assess the effectiveness of insulation in homes and commercial buildings remotely, to find air in-leakage in homes and commercial spaces, and to evaluate commercial building envelopes.

Roof moisture can be caused by poor design or installation, use of unproven or inappropriate materials, and lack of maintenance. Roof moisture leaks frequently into the roofing material, and then soaks the insulation underneath. This could cause a slew of costly building maintenance problems, and timely detection is the key to avoiding them. If unchecked, roof moisture slowly destroys the roof, the membrane below, and the insulation, and leads finally to rusting of metal decks and fasteners, which are the roof's support structure. This also causes leaks which progressively worsen. Wetness makes the insulation ineffective, and repairs are not effective unless they replace both the wet insulation and its cause, leaky roof material. Whether it is wet from an external leak or internal condensation, once wet, insulation rarely dries out. Wetness and leakiness also increase energy consumption since wet insulation is less efficient at conserving heat (or air conditioning, alternately). For all these reasons, homeowners, landlords and corporations demand comprehensive and reliable techniques for spotting roof damage as early as possible. Infrared thermography is one of the techniques available.

There are four general methods to find moisture-damaged insulation in a roof. Coring or cutting are time-consuming if analyzing an entire roof, and are also destructive. The three other methods are non-destructive; they are nuclear detection, capacitance, and infrared thermography. Thermography is by far the cheapest, can survey large tracts of roof and insulation faster, and is contactless.

Wet and dry insulations have different abilities to conduct, absorb, and retain heat. Exposed to a clear, sunny day, wet insulation will absorb more heat, and retain heat longer. Conversely, wet insulation will remain colder, longer, in cold weather. Once the wet areas are located, inspectors can mark them with chalk or paint, and roofers can replace or patch those areas.

Despite its advantages, roofers and thermographers explained that there are two drawbacks to the use of infrared cameras in assessing roof moisture and wet insulation. First, IR thermography is weather dependent. It will not work if the roof is recently wet, or if winds exceed 15 mph. Shaded areas also can be difficult to image, since they do not receive optimum radiation from the sun. Diagnostics can not be conducted when the weather has been cloudy or during the late summer or early spring. Second, certain materials simply do not image well with IR thermography. Some insulators do not absorb moisture, but rather let it sit on the roof. Foam insulations do not absorb water well; roofs insulated with perlite, wood fiber, or fiberglass work better. On the other hand, some roof materials prevent good IR profiles from being acquired. Uninsulated wood or concrete decks, for example, also image poorly, according to thermographers we contacted. On ballasted roofs, the stone is so heavy that it overshadows images of moisture in insulation. Gravel, however, is better because it is more thermally connected to the insulation. Aluminized roof coatings have low emissivities and are therefore difficult to image. Despite these shortcomings, however, roof contractors and building engineers say IR thermography is indispensable in their non-destructive evaluation of roofs.

A second area of building and structure diagnostics to use IR imagers is testing the efficiency of insulation in private homes and commercial spaces. In these applications, engineers walk around a building or home with portable IR cameras, looking for areas within walls or along windows and doors where outside air is leaking in. IR cameras could search the joints of roofs and walls, electrical outlets, outer corners of homes, windows around sealings and frames, joints of floors and walls, and joints of chimneys and roofs.

A federally funded program has led development of this application. The US Department of Energy's Weatherization Assistance Program (WAP) seeks to improve the energy efficiency in thousands of residences of low income people. Emphasis has been on the most inexpensive yet comprehensive instruments to assess energy efficiency, since program costs, including support costs, administration, labor and materials must average, by law, no more than $1,600 per housing unit. Since 1988, over 100 thermal imagers have been purchased by 25 states for thermal evaluation of homes for air leakage. Imagers have been used not just to evaluate homes thermally, but to test the workmanship of contractors who have skimped in the past on installing insulation.

The Swedish government is also pioneering this type of research in conjunction with Agema Infrared, through its Department of Energy in the Ministry of Trade and Industry. The Swedish project, entitled "Renovation Concepts for Private Houses," seeks to decrease energy used for home heating by 25-75 percent. It uses thermography and supporting methods to scan homes for cold bridges, insulation and installation defects, structural defects and air leaks which cause home heat loss. Sweden estimates that up to ten percent of its total energy consumption in 1988 was used to heat homes. Two thirds of those homes were built before the 1974 energy crisis, and are not nearly as energy efficient as they should be. The Swedish authorities are using thermal imagers to find thermal leaks in walls or around windows, either because of voids in insulation or simply lack of adequate and efficient insulation.

A third type of specific application in the family of building and structure diagnostics is the assessment of flow and regulation of air distribution systems in homes and offices. Since air vents and ducts typically have the same temperature as the air running through them, IR inspections could be used to determine that systems are operating effectively to regulate room temperatures and to evaluate the overall condition of the system. Recommendations for adjustments, repair or replacement of components, and vent relocations can be made with the support of quantitative data. This application is limited, however, since insulation and air in-leakage are far more common than problems with air distribution systems.

A final application under the heading of buildings and structures is the use of infrared cameras, in conjunction with air leakage tests, to find leakage in large factories which have been retrofitted with building envelopes. In one case study, a satellite testing facility which had been retrofitted with a metal cladding envelope had its heating costs reduced by thirty percent following plugging of leaky areas identified by thermal assessment. In that building, as in many retrofitted buildings, problems occurred where additions joined together. Designers and contractors did not ensure that the building would remain air-tight with the addition of a metal-cladding envelope. Since the building had higher humidity than outside air, rust and corrosion began to occur at points of air leakage, and would have been very costly to repair.[38]

[38] Antonio Colantonio, "Metal Cladding Envelope Problems, Retrofit Solutions, and Quality Control Investigations," Thermosense XIV (SPIE, 1992) pp.64-71.

(iii) Materials, Metals, and Composites. The most sophisticated and demanding family of applications of IR imaging in NDE is the assessment of metals, composites, and complex materials. Thermography is especially capable of making images of subsurface defects in opaque solids. By contrast with most other infrared applications, which image the superficial temperature to a depth of at most 2 mm, this application images deeper into a material, up to a few inches. It accomplishes this by using complex yet reliable computer modeling and analyses which sort through images and determine what percentage of any given pixel's temperature is the result of different layers in the test material. In effect, this advanced NDE technique quantifies and profiles voids or less dense spaces within composite materials much like applications in underground imaging of buried mines, pipelines, archeological remains, etc. discussed in the remote sensing section.

The most widespread technique used for this application is pulse-echo or thermal wave imaging. The test material is exposed to rapid pulses of infrared heat, and reflected IR energy contains copious information about the test material's structure, depth, uniformity, and consistency. Imaging periods last about five seconds, and no longer than 30 seconds. Thermographic tests require machinery with extremely fast imaging speeds, at 200-500 Hz. Materials which dissipate heat very quickly, such as aluminum, require cameras which operate up to 1 MHz. Heat sources usually apply heat either in the form of long, even pulses, or in the form of short pulses followed by long rest periods. Light pulses are produced by either quartz lamps or, increasingly, laser beams focused on the material's surface. Pulses or waves of IR heat are emitted from the surface of the material bombarded with IR pulses. Raw thermal data is acquired by advanced IR systems using focal plane arrays of about 256 X 256. Thermal data is processed extensively to yield a profile reaching several layers beneath the surface.

The most prevalent current use for this technique is to assess aging aircraft panels for subsurface defects, ranging from cracks and disbonds to delaminations or corrosion. Both the Air Force and Federal Aviation Administration have programs underway to assess thermography for inspection of aircraft panels, particularly lapjoints where faults are likely to occur. In airframe lapjoints, overlapping layers of aluminum are glued with an epoxy layer, which is reinforced by rivets. Degeneration of the epoxy layer, which is the most prevalent airframe corrosion problem, usually occurs around rivets and eventually becomes visible on the outside aluminum surface. Disbonds finally lead to cracks in the aluminum if unrepaired, and cracks have been known to suddenly link up and cause sudden failure of the part.

The two current aerospace inspection techniques are either unassisted visual inspections, or point measurements using a small hand-held ultrasonic probe. Eddy current detection of cracks at rivets and sonic bond testers, both offshoots of ultrasonic technology, are thermography's main competitors. But ultrasound is only effective after cracks reach the aluminum's surface. Thermography, by comparison, detects epoxy deterioration itself, underneath the aluminum, before it manifests on the aluminum surface. This is a major advantage over ultrasonic techniques. Thermography is effective because a disbond between layers of a laminated structure will prevent heat from penetrating from the surface layer to the subsurface layers and will result in an increase in surface temperature over the disbond. Thermography is also non-contact, whereas ultrasound requires coupling liquid to be placed on the test material to conduct its sound waves. Whereas ultrasonic inspection of an aircraft requires about 22 days, thermography accomplishes the task in two and a half.

Composites which range from the exotic --such as carbon-epoxy polymer composites for aerospace uses -- to the mundane -- such as routine fiberglass -- can be inspected in a similar manner for subsurface defects, defect propagation through successive layers, cracks, and corrosion. This is an extremely software-intensive and analytic application in which varying temperatures and varying times of return of thermal echoes reveal interactions between different layers in a material. For sophisticated applications with graphite-epoxy, for example, thermal wave tomography creates a three-dimensional image of damage within material. The most mundane application for pulse-echo thermal wave imaging could be detection and assessment of automotive paint damaged by rust or stone impacts. Since automotive paint is a multi-layered coating, it lends itself to subsurface-imaging, as well as aerospace aluminum and epoxy composites.

Another family of non-destructive evaluation techniques which could use infrared detectors is stress photonics, also called thermoelasticity. In these applications, metals or composites are bent or stressed repeatedly while thermal cameras simultaneously profile temperature distributions in the test material. Stress points raise temperature about a thousandth of a degree celsius, but an image can be compiled with a camera sensitive to 0.1°C through repeated stressing and imaging. Although immediate applications under investigation include testing aircraft aluminum and fiberglass panels or support structures for their stress-worthiness, the mid-term applications include testing support structures for bridges, buildings, and roadways. Research thermographers at Stress Photonix in Detroit, MI were especially optimistic that IR imagers could help detect early deterioration in aging bridges, where corrosion usually leads to premature decreases in the load ratings and early retirement.

Likewise, thermography can test for uniformity and even thickness of laminates and coatings. In a pioneering application, aerospace companies have used thermography to test ceramic thermal barrier coatings in engines. Ceramic coatings were added to improve gas turbine efficiency while reducing metal temperatures. The same coatings are now being added to common diesel engine pistons for emissions reduction, thermal fatigue improvements, and fuel economy benefits. A common source of failure of these coated parts is separation of either the coating from the metal, or coating layers from one another, as a result of thermal stress in engines. Therefore, periodic thermographic imaging of thermally coated pistons, or of test pieces, is becoming widespread. Inspection is done by pulse-echo thermal wave IR imaging.

Thermography has advantages over competing techniques for the inspection of laminated and coated products. Fluorescent dye penetrant inspection, ultrasonic, and acousto-ultrasonic inspection have all been considered, according to researchers, but IR thermography produces clearer images with better contrast, and acquires them at least five times faster. Ultrasonic scanning, the most pervasive NDE technique, does not usually image coatings well, because coating porosity and multiple coating layers result in severe attenuation of the ultrasonic signal. Thermography has emerged as the leading technique for imaging laminates. Thermographic researchers explained that IR cameras could eventually image much more mundane laminates and coatings, including coatings on glass, optical lenses, furniture, table tops, metals, and plastics. These applications with pervasive appeal could become available within three to five years.

A current down-to-earth application has been the infrared inspection of aircraft engine parts. General Electric Aircraft Engines (GEAE), a component of General Electric Co., has pioneered this work over the past ten years. GEAE designed a system, originally with US Air Force funds, to non-destructively test high-performance engine turbine blades. Many of GEAE's aircraft turbine blades contain internal passages and surface cooling holes that allow them to operate at temperatures above the service limits on the blade materials. The two techniques used originally for inspection of those passages and holes for blockage were manual and inexact. In one technique, operators forced a high-pressure stream of water through each blade, observing the water which exited the holes. They also used pin gauges to verify the size of each hold, and to check for blockages. These techniques were labor intensive, slow, expensive, and inexact.

In 1980, GEAE designed an infrared inspection module (IRIM) with funds from the Air Force. NDE experts had shown that when hot air was injected into a finished blade's cooling passages and holes, an infrared camera could detect temperature differences on the surface of the blade. Properly functioning surface holes would show up in thermograms as "warm," because air was circulating well through them. "Cold spots" indicated blocked passages, and those parts were scrapped. GEAE's two newest IRIM's were installed in 1989 at the US Air Force's San Antonio Air Logistics Center (Kelly AFB, San Antonio, TC), where the Air Force performs major maintenance and overhauls on a wide variety of engines. An older system, also developed with AF funds, operates at GEAE's air foil plant in Madison, KY.

A related infrared application at GAEA, which falls between NDE and process control, is the inspection of holes (which are used for cooling) which have been freshly drilled by automated lasers, in a variety of turbine blades. The drilling occurs about halfway through the production of the blades. A robot loads each blade into a part manipulator, which rotates the drilled parts into six to twenty positions, where thermal images are taken. Software then automatically compare each image with preset tolerances for hole size, position, and thermal characteristics. Blades with missing or blocked holes are automatically transferred to a "reject" conveyer for further testing and rework. GAEA estimates that when the laser drilling equipment is working at full capacity, turning out 3,000 blades a week, infrared inspection saves them

$2,000-$3,000 per week in labor, rework, and scrap by identifying substandard blades before they undergo further processing (such as coating, EDM drilling, or dovetail grinding).

Market Analysis. The non-destructive evaluation market for IR detectors is growing, but will remain specialized. We project separate fates for the three distinct family of applications -- IC board inspection, building and structure inspection, and materials evaluation.

The market for inspection of IC boards, in particular, could flourish with the introduction of high-speed focal plane array-based cameras within two to three years. Thermal imagers offer substantial advantages over conventional point-probe testing, and could permit inspection of PC boards at any stage of manufacturing. Installation along assembly-lines could become a substantial and profitable market. Executives we interviewed predicted that annual sales, after about 1995, could reach 5,000 units a year. All told, the market could be worth over $300 million a year through the end of the decade as electronics companies invest in thermographic inspection equipment.

Units would not need the extensive, multi-purpose software now used in most advanced IR systems on the market; they would only need to conduct IR image subtraction. IR systems for integrated circuit board inspection should stress technology in the detector and camera, but perform only routine thermal processing. This means that the focal plane array can bear a larger share of the cost in $60,000 systems, while software, a significant cost factor, is reduced. All the executives we contacted estimated that systems designed for electronics companies would use sophisticated, high sensitivity (0.1°C), video-rate imaging (60Hz or better) and high resolution (320 X 320) IR detectors which image in the 8-12 micron range. Staring detectors offer the advantage of high imaging rates and high sensitivity, all of which increase throughput and accuracy in testing IC boards.

The outlook for building and structural insulation, leakage, and roof assessments is more sedate. Although several consultants swore by scanning infrared detectors, the majority of users are small-time roofers, insulation contractors, or building engineers who would be loathe to invest in systems costing over $20,000. These applications require simple IR cameras hooked up to video recorders, without any diagnostic software. Images would be subjectively interpreted by trained engineers. Although second generation infrared cameras would be a tremendous technical boon to an industry which traditionally employs vidicon-tube cameras, it could be a challenge to produce sophisticated IR cameras cheaply enough to gain widespread acceptance. A major cost saver is that systems used in this niche do not need to determine precise temperatures in pixels. From interviews with industry officials, we estimate that all versions of building and structural applications could consume about 1000 thermal cameras a year, starting right now; a total market ob about $20 million a year. Although IR cameras are unopposed by competing diagnostic techniques, they must be inexpensive to penetrate this market dominated by vidicon systems.

Finally, there could be substantial growth in NDE applications of IR imagers to assess materials for voids, inclusions, delaminations, defects, cracks, and other non-uniformities. Most focal plane array IR detectors currently in commercial use are sold exclusively for the NDE of materials. This laboratory-style market requires highly sensitive (<0.1°C) and extremely rapid imaging capabilities (up to 500 Hz). Systems typically cost in excess of $100,000. Less than 1,000 thermographic systems exist in labs, and more widespread applications are a long-term prospect. It would take at least five years, according to experts we interviewed, before pulse-echo thermal wave imaging bridges the gap from inspection of aging aircraft to routine inspection of fiberglass, car paint, diesel engine pistons, etc.

If those more widespread applications did catch on after about five years, we estimate that 500 units could be sold annually at current prices (about $100,000), rising to 1,000 if unit prices fell at or below $50,000, which is a more realistic market price.. The total market, which would develop after about 1997, would be worth $25 million annually.

In summary, NDE encompasses three families of applications with little crossover in system design or market outlook. Total market activity could total $345 million in the mid-term, led by two applications: IC board inspections, which could sell in very large volumes, and NDE of materials, which require fewer, but more expensive machines. More widespread commercial applications of IR systems for materials inspections may be far off or may not materialize. Building and structure diagnostics can rely on cheaper and less sensitive equipment, and may therefore never be ripe for advanced systems.

<u>Suppliers</u>. The same firms which prevail in predictive maintenance, biomedical, and remote sensing markets play a hand in the NDE market as well. The most active companies, in order of market share, are Inframetrics, Agema, Amber, and FLIR systems.

Only one company specializes in thermographic machines for NDE. **Bales Scientific**, in Walnut Creek, California, designs NDE workstations which combine a UNIX operating system and sophisticated analytical software with a scanning IR camera. Its single-point MCT-based cameras sell for about $70,000-$100,000. The basic BSI TIP system images at only 30 Hz, but Bales claims it is sensitive to 0.02°C at 35°C. It operates only in LWIR, and is cooled with liquid nitrogen. Like all liquid nitrogen cooled systems, the BSI TIP can not be turned upside down. Therefore, it can not scan underneath the belly of an airplane, which is a necessary step in the inspection of airplane panels. Its field of view is 10 to 30° horizontal, and 5 to 20°C vertical.

By comparison, vidicon camera manufacturers sell much less expensive systems for building diagnostics. For example, **ISI Group** in Albuquerque, New Mexico, sells the

Videotherm 91S infrared imaging system for $17,500, the Videotherm94 for $23,000, and the Videotherm 96 for about $21,300. The Videotherm 96 offers digital temperature read-out at one point, and pictures of visible images along thermal images. **Electrophysics**, in Fairfield, New Jersey, sells the most popular line of vidicon cameras, called Pyroviewers. The basic vidicon camera Model 5400-01 and Model 5400-02 sell for $14,600 and $17,600, respectively. The more expensive 5400-02 does not require panning and can be fixed mounted. With two other cameras by Electrophysics, users locate hot-spots in thermal image mode for which they want temperature measurement, and the camera switches to visible light image mode while it measures absolute temperature. Model 5500-01 costs $18,500, and Model 5550-01 $21,500. The more expensive system does not require panning and can be fixed mounted.

## Predictive Maintenance

The single most highly developed market for sophisticated IR sensors is in predictive maintenance (PM). For the past 25 years, infrared detectors based on a wide range of technologies -- pyrovidicon, SPRITE, photodiode, photoconductive -- have been used extensively as a method of predictive maintenance in industrial plants, factories, nuclear power plants, electric power generator facilities, and foundries. IR detectors can be used to monitor plant equipment, locate overheated or abnormally cold components, diagnose functional problems, assess the urgency of repair, and prescribe corrective measures at any plant operating either mechanical or electrical equipment. Individuals who were interviewed for this section are listed in Appendix J.

The PM market could grow tremendously if more advanced, IRFPA-based cameras were introduced. We predict the market could reach over $1 billion in just five years. Every single operator, manufacturer, and thermography consultant whom we interviewed claimed that older vidicon-based and single-point scanning systems which now prevail were antiquated, and that staring detectors with radiometric ability were the "wave of the future" which would overtake most existing applications, and open up altogether new ones, all of which are described below. Even though the few sophisticated IR detectors on the market which are radiometric (able to determine absolute temperature in each pixel) cost about $100,000, they have already begun to revolutionize predictive maintenance. For instance, insurance companies are requiring increasingly that nuclear power plants, and plants with large-scale machinery, thermally inspect their critical equipment at least quarterly, both as a means of preventing failures and to certify lifetime extension of the older equipment which they insure. Nuclear power plants claim that by thermally inspecting their electrical equipment, they save in three years in insurance and shutdown fees in three years what it takes to purchase a top-of-the-line IR predictive maintenance system. Overall, staring IR detectors with radiometric qualities, such as MCT-based IRFPAs, are anticipated with great enthusiasm by predictive maintenance engineers.

In this section, we discuss how thermography is integrated into a comprehensive predictive maintenance program, and how a basic thermal inspection is conducted. The difference between qualitative and quantitative methods of PM are discussed, and we explain that the market is moving overwhelmingly towards the more complex, radiometric and quantitative mode. We discuss the full range of current and upcoming applications for thermal imagers in predictive maintenance of machinery and electrical machinery. In the market analysis section, we predict that radiometric thermography in PM will continue to gain momentum and offer substantial profits through the mid- and long-term. This is because thermography offers substantial cost savings to predictive maintenance engineers, because insurers are requiring increasingly that plants use thermography, and because sophisticated IR detectors based on MCT offer substantial advantages over current systems. Finally, we discuss critical issues in system design which could adapt MCT-based detectors to the growing PM market.

IR Thermography in a Comprehensive Predictive Maintenance Program. Predictive maintenance is the periodic testing, monitoring, and diagnosis of equipment at a factory, plant, foundry, or power generation facility in order to prescribe maintenance and replacement of equipment components before they fail. This differs from *preventive* maintenance, which is the actual replacement of parts, readjustment and cleaning of key components, etc. on a regular schedule to prevent catastrophic machine failure. Predictive maintenance techniques, like thermography, help hone the cheapest and most failsafe method of part replacement, cleaning, repairing, and tuning. A comprehensive PM regime keeps machinery and electrical equipment running at their optimum efficiency, minimizing the chance of failure or outage. Failed equipment and shutdowns can cause much more damage and be more costly to repair after-the-fact than if the impending failure had been detected beforehand and nipped before it caused shutdown and outages. The best diagnostic techniques allow equipment to continue to run while being testing, so as not to cause downtime or lost production.

The practice of thermography in predictive maintenance is slightly different between mechanical and electrical engineers, although both fields employ identical thermographic equipment. In PM of engines and motors, working machinery is scanned for hot or cold spots which indicate improper or excessive wear which could be caused by poor or excessive lubrication, misalignment, overuse, poor tuning, looseness, excess vibration, leaky insulation, etc., and may predict an impending failure of a component. In PM of electrical equipment, on the other hand, hot or cold spots denote components with excessive or substandard resistance caused by loose connections, corroding wires, overheating transformers, poor adjustments, faulty connections, etc.

In both these branches of predictive maintenance, IR thermography is used in concert with other techniques. A complete predictive maintenance regime for machinery, in particular, rests on three pillars. First, vibration analysis detects whether a machine is balanced and aligned correctly. Any corrosion, blockage, overheating, or misalignment would cause the machine to run off-balance and therefore deviate from its normal vibration signal. If misalignment has been diagnosed in a machine, the same vibration analysis equipment then continues to monitor the machine as it is worked on to correct the alignment. This is the most prevalent PM technique employed in this country, and is regulated by the American Society for Non-Destructive Testing (ASNT). A second method of PM is lubrication analysis, also called ferrography, in which oil lubrication from machines is sampled and tested by analytical equipment like a spectrometer, for traces of metal which has been worn off from gears, motors, valves, etc. A high metal content in the oil indicates excessive wear on a machine's parts.

IR thermography is the third technique in predictive maintenance of machinery. Sophisticated thermal imaging equipment views machinery in operation, searching for atypical thermal signatures for various parts of that machine. An abnormal thermal profile can indicate corrosion, blockage, improper alignment, excess rubbing of gears, improper lubrication, etc. PM is a dynamic application in which the IR camera is constantly adjusted and moved to obtain the best contrast between a hot or cold area and surrounding machinery. The application is also dynamic because many overheating problems are time-dependent in that they will peak after a certain time, and be easily detectable, and then begin to dissipate and radiate into other mechanical parts, obscuring their point of origin. Therefore, some thermographic inspections are conducted at engine start-up, such as searching for pinhole leaks in insulation. The same thermographic equipment continues to monitor machinery while it is being repaired, indicating whether maintenance has cured the atypical heat signature of the engine part.

All three of these techniques -- vibration analysis, lubrication analysis, and thermography -- are employed by a vast array of manufacturing companies in the energy, petrochemical, plastic, metal, and printing, chemical and process industries, among others. Any large and sophisticated plant uses some mixture of these three techniques to manage the maintenance of mechanical equipment. Although there are several large US firms which contract out for thermographic inspections, about half the units sold in the US to monitor machinery are operated by companies themselves by trained personnel.

In the predictive maintenance of electrical equipment, the traditional method has been for an electrician to test individual circuits suspected of having atypical and high resistance which leads to watt dissipation and voltage drop. Unrepaired, high resistance leads to early retirement of parts and substandard performance of motors connected to those electrical components and possible part failure. This system of individually testing and diagnosing electrical leads and components is time consuming, requires the components to be shutdown or bypassed during the test, and is costly.

Infrared thermography, on the other hand, is cheaper and more effective because the components are sensed passively without being shut down, bypassed, or dismantled, and hard-to-reach components like motor-busway connections can be imaged. An additional benefit offered by thermography is that high voltage components can be monitored from a safe distance to avoid contact or exposure to equipment suspected of faulty operation, a reason why many sensitive components are not inspected as often as recommended.

In fact, the capability to thermally map transmission lines, switchgear and power generation equipment, in real time and without contact, has allowed thermographic plant-condition monitoring to develop over the past 25 years to a point at which it is now a universally accepted PM technique in power-facility operation. In nuclear power plants, in particular, where the stakes are very high and there is no margin for error in predictive maintenance regimes, thermographic IR is a virtual necessity.

How are routine thermographic inspections conducted on machinery and electrical equipment? Engineers enter a factory with portable, lightweight, and sensitive (.1°C) infrared imaging equipment, which images in real-time, at 30-60 Hz. Most IR camera equipment is shoulder-portable, but some workstation-based systems travel on wheels. Engineers remove the protective dust panels from equipment, exposing motors and electrical equipment. They then view the equipment thermally, while in operation, recording the thermal images either in digital form for statistical analysis, or on video. Engineers view the thermal profile through either an eyepiece or video screen during the entire operation. Some portable thermal imaging systems have analytical software to process digital images and do image subtraction or addition on the spot; other systems have the camera record data which is then processed at a remote IR workstation.

During an initial survey, inspection personnel go through a facility to establish and record "baseline" signatures of all machinery, switchgear, and control equipment suitable for thermographic inspection. In addition, thermographers make note of anomalies that appear where experience tells them they should not, in the case of, say, a hot relay among several identical relays. On subsequent visits, current thermal pictures of the equipment are compared with the baseline image; deviation beyond an accepted standard indicates excess wear. Comparing current thermal images with baseline ones, and predicting when parts needs to be replaced, is called trending. At the majority of plants using IR for predictive maintenance, each component is surveyed at least once a year. In nuclear power plants, every significant component is inspected quarterly, because the entire industry is rightly "hyper-vigilant," as one source stated.

Thermographers search for two categories of abnormal thermal profiles of electrical and mechanical components. First, they search for minor abnormalities in vital components, such as motor connections, motor terminal housing, main motor bodies, transformers, switchboxes, etc. which would cause a major shutdown or failure if unattended. Second, they search for major abnormalities in auxiliary components which are not vital to day-to-day functioning, but which could likewise be costly to replace if they failed.

While searching for these two categories of abnormal thermal profiles, it is typical to categorize an infrared finding into one of four categories, according to thermographers we contacted. They range from minor to critical, and the deciding variable is the temperature rise of a component above its rated normal operating temperature. In normally loaded electrical circuits, for example, the categorization is based on temperature rise above a reference value, typically a like component or different phase. In certain situations such as lightly loaded circuits that are expected to operate satisfactorily at high loads, the value judgment may result in a critical finding for a very small temperature rise. In the case of vital, high voltage power distribution equipment, for example, the joint ANSI/IEEE/NEMA temperature standards are presented in table two below:

**Table 2. Joint ANSI/IEEE/NEMA Standards for High Voltage Power Distribution Equipment**

| Temperature Rise over Ambient | Remarks |
|---|---|
| 0 to 10°C | Corrective measures should be taken at next maintenance period. |
| 10 to 20°C | Corrective measures required as scheduling permits |
| 20 to 40°C | Corrective measures required ASAP depending upon the class of load carried and the severity of temperature rise in this range. |
| 40°C and over | Corrective measures required immediately.[39] |

Similar standards exist for motor components also. Engineers then make a cost-benefit analysis to assess when to correct the abnormal circuitry or motor component, and design an overall preventive maintenance schedule. In the case of electrical circuity, one thermographer explained that the following questions are considered before deciding on a course of action when a component is found to have an atypical thermal signature:

- What is the resistance at the connection or in the circuit?
- What voltage drop is there across the connection or cable?
- What is the net result of the voltage drop?
- What is the center temperature of the wire?
- How does the center temperature compare to the wire rating?
- What is this doing to the motor?
- What is the cost to fix this situation?
- What is the economic penalty of not fixing it?
- How close to failure is it?
- What failure mode will it present? [40]

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[39] P. Grover, "Applying ANSI/IEEE/NEMA Temperature Standards to Infrared Inspections," Thermosense XIV (SPIE: 1992) pp. 101-107.

[40] R.D. Lucier "Predictive Maintenance for the 90's-- an Overview," Thermosense XIV (SPIE: April 1992) pp. 35-41

Qualitative vs. Quantitative PM. In the thermographic PM of both mechanical and electrical equipment, users choose from qualitative and quantitative methods. Qualitative measurement compares the infrared pattern of one component to that of an identical or similar component which is under the same or similar operating conditions. This comparison is performed by viewing several identical or similar components through an IR camera, recording their thermal signatures, and searching for different thermal patterns. For example, several identical switches may be positioned side by side, and have identical loads, so if they are viewed simultaneously, and one appears hotter than the others, then it is likely malfunctioning. In qualitative thermography, anomalies are identified by the intensity of temperature variations between any two similar objects; it is not necessary to determine absolute temperature values for the components being tested. This technique is quick and easy, and does not require the complex algorithms on more sophisticated, quantitative IR cameras to compensate for variations in room temperature or surface emissivity. This method dates back to the advent of IR thermography in PM in the early 1970s when instruments could not ascertain absolute temperatures. The result of this type of measurement is limited to identifying immediate problems: it does not provide a precise level of severity. For simple applications, such as the diagnosis of the misaligned gear in an engine which is known to be functioning unevenly, qualitative thermography has its place. Qualitative measurements have been conducted in large utility or process plants where hundreds of nearly identical components are surveyed. Similar machines will have nearly identical emissivities, operate in identical ambient temperatures, and wear similarly, so the temperature differential between two or more pieces of equipment can be compared without precise temperature measurement.

While qualitative measurements detect impending part failures, it is *quantitative* measurements that have the capability to determine severity, and help *trend* abnormalities in equipment which is atrophying slowly, but at levels not readily seen. Quantitative PM requires exact temperature measurements in each pixel of view, and it is a much more complex application for both the infrared detector and accompanying software. If thermal images of a component are compared over several months or a year, trends can be identified by plotting temperature over time. Slow decay, wear, blockage, or corrosion, for instance, can be detector long before parts actually fail.

An example of quantitative measurement is the predictive maintenance of a solitary piece of equipment, such as a motor, which does not have similar components operating nearby. The absolute temperature of the motor casing is determined by the thermal imager. This provides indication of whether the motor is operating within its design temperature when referenced to temperature data on the motor's nameplate. Another example would be monitoring an electrical switch in a nuclear power plant to detect deterioration and watt dissipation as early and accurately as possible.

However, these measurements are considerably more difficult to obtain. For an accurate temperature value, several factors must be taken into consideration such as atmospheric attenuation, ambient reflections, and emissivity. Measuring some of these factors has been complex and time consuming, according to thermographers we contacted. The two limiting factors are determining the exact emissivity of a component, and using complex algorithms to compute exact temperature. Both these hurdles are being overcome by commercial producers in response to very large market demand for quantitative systems. To determine emissivity, each plant usually determines precise default values for the emissivity of their equipment. It is possible to check the emissivities of a few of the most commonly encountered materials in the plant to assign a default value which can be used when inspecting components with these materials. For example, one company described by a thermographer used defaults valued for aluminum (motor boxes, aluminum panels) of 0.2, for copper (bus bar) of .4, for stainless steal (bolted connections in electrical equipment, shaft) of 0.6, and other materials (painted surfaces) of 0.9. Since every plant differs in the dirtiness, polish, and paint of their machinery, emissivity values are unique to each plant.

The software packages and algorithms which accompany IR systems for PM are very extensive to make precise temperature measurements. As an example, the algorithm used by the AGEMA 870 consists of 11 variables manually entered by the operator, numerous stored constants, as well as the equipment's thermal level, range, and isotherm settings. Even at the level of detail at which calculations are made in the software, there are already several simplifying assumptions, including treating the object as opaque (no transmitted radiation) and that the surrounding area is a uniform ambient temperature. The impact that these assumptions will have on the accuracy of the temperature read-out is dependent on the object's actual emissivity. In addition, the object's emissivity itself must be estimated. For very high emittance objects, the resultant error is minimal and techniques to improve surface emissivity are effective for two reasons. They raise the emissivity to a known value which can be entered as an input parameter, and the error introduced by the simplified assumptions is minimized.

The market for IR machines in predictive maintenance, according to every thermographer we surveyed, is moving overwhelmingly towards quantitative analyses. This is true for two reasons. First, exact temperature measurement can precisely indicate trends in deteriorating components, which can be subjected to Fourier Transform Image Reduction (FTIR), plotting temperature over time. To give the earliest prediction possible of deterioration in components, quantitative assessments are necessary. Secondly, standard operating temperatures for electrical components, not to mention rot[illegible] mechanical equipment, have been set by at least 2[illegible] organizations in the US, which determine the standard ambient temperature, the maximum temperature rise allowed above the ambient, and the total allowed temperature, which is the sum of ambient and maximum temperature for equipment. Only the quantitative measurement method can determine precise temperatures to ensure compliance with those standards.

All the major companies working on IR units for predictive maintenance have endeavored to develop radiometric equipment for years. The current systems offer tradeoffs between scan speed and sensitivity because they are based on single point scanning photoconductive cells, usually of MCT or InSb. No system on the market offers sensitivity and real-time resolution for under $100,000. Every thermographer we interviewed explained that there would be tremendous market potential for radiometric systems which could deliver quantitative data for less than $100,000.

Applications. Although the general applications of IR detectors in predictive maintenance have already been described, we can expand the list of specific applications in monitoring machinery, and electrical equipment.

Any type of rotating machinery can be monitored for mechanical stress through IR thermography. The list of specific mechanical components which can be scanned is short, but absolutely every factory, whether large-scale utilities or small-sized assembly-lines, contains engines which use these moving components, often in dozens of pieces of identical equipment. When any engine part begins to corrode, leak, or is low on lubrication or surrounded by dirty lubricant, unbalanced or misaligned, its thermal profile will differ from the norm. For example, when a transformer is low on oil or a bearing begins to dry, heating invariably results. Or when the insulation of a cooling vessel begins to fail, cool areas appear on the outside surface. Infrared equipment can be used to check bearings on rotating equipment, including motor bodies, motor terminal housings, shafts, coupling pumps, ball bearings, bearing ends, etc. Thermography can also be used to inspect condensers and hydraulic systems and balance HVAC system outputs, and to check heaters, heat exchangers, radiators, cooling systems of stationary equipment, molds and curing units, compressors, diesel engines and exhaust manifolds, conveyer belts, drive gears, drive belts, and fluid transport lines. In the rebuilding of motors and generators, thermographic inspections of motor windings and cores have proven an indispensable help.

Specific industries could also inspect machinery unique to them. A coal company, for example, inspects thermographically final drives, crushers, conveyor belts, and boget pins and d-pins in high drive tractors, etc. As an adjunct, liquid levels can be remotely determined on gas tanks, water tanks, vats, halon systems, etc. Petrochemical industries, in particular, depend on thermography as a backup to existing instrumentation for finding fluid levels in tanks, especially during critical transfers.

Thermography can be used to inspect steam traps and steam pipe insulation. At the heart of steam engines is a steam trap which transfers condensate back into the heating unit, and these are often the earliest parts to become blocked by dirt, corrosion, unwanted air venting, and back pressure. Thermography can be used to inspect refractory for early stages of breakdown, and to locate blockages in boiler or heater tubes. Under many conditions, it can also be used to locate underground steam lines, insulation breakdown, and steam leaks. All these components can be viewed by thermography.

The majority of electrical PM applications are in high and medium voltage switchgear, circuit breakers, and transformer stations. This includes board connections, control circuits, bus connectors, busways, bush assemblies, motor control centers, overhead lines, terminal housing, low voltage panels, exhaust fans, fuses, fuse clips, lug connectors, knife switches, rectifiers, transformers, contacts, breakers, fuse connections, splices, battery banks, and bus bars. Physically inaccessible terminals such as motor- busway connections can be viewed remotely. American Risk Management Services, for example, suggests that six types of electrical equipment be inspected:

1. Power Distribution and High Tension Lines
2. Substation
    - Transformers
    - Transformer Bushings
    - Capacitor Bank Connections
    - Disconnects
    - Fuse Clips
    - Bus Connections
    - Relays and Breakers
    - Meter and Control Connections
3. Electrical Vaults
    - Breaker and Contacts
    - Bus and Fuse Connections
    - Fuse Clips and Friction Connectors
4. Motor and Generator Control Center
    - Connections and Contacts
    - Molded Case and Air Breakers
    - Bus Friction Connectors and Fuses
    - Thermal Overloads
5. Enclosed Bus Runs
    - Bolted Connections
    - Conductor Fatigue
6. Generating Stations
    - Generator Windings
    - Generator Brush Riggings
    - Generator Feeders to Primary
    - Breakers and Transformers
    - Exciters
    - Voltage Regulators
    - Relays and Metering

Several thermographers told us that electrical inspections do not currently include various components which should be tested. High-voltage components are usually overlooked because systems are well insulated and protected, and PM engineers consider it very dangerous to open switch cabinets, starter cabinets, or any high-voltage distribution closures if they suspect overheating problems. Components which operate with voltages over 480V (such as 2300, 4160, 13,800 and 115,000) are often overlooked for these reasons. As thermography gains the confidence of plant PM engineers, these components will be inspected more frequently in the future by thermographers. Some of the high-voltage systems normally *not* inspected (and the reasons they are not inspected) are primary feeder cabinets (interlocked), main and tie switches (interlocked), transformer primary fused disconnects (interlocked), transformer primary coil taps (bolted covers), transformer secondary coil taps (bolted covers), transformer secondary bus compartments (bolted covers), power factor correction capacitor fused disconnects (interlocked), high voltage motor primary fused disconnects (interlocked), and high-voltage motor starter cabinets (interlocked). Other systems *sometimes not inspected* are 480V main bus on breaker cabinets (bolted covers), 480 V main and feeder breakers (interlocked), high-voltage and 480 V cable trays (bolted covers), closure covers on power factory correction capacitor cans (bolted covers), high-voltage motor tee box covers (bolted covers), and large generator and exciter brushes and slip rings (bolted covers). Within the next few years, we predict that these components will begin to be inspected by thermographers.

All the components discussed in the sections above, whether mechanical or electrical, are found at plants and factories worldwide. Every industry can benefit from thermographic inspections of their machinery and electrical equipment, ranging from the petrochemical, to the power generating, paper, steel and metal, plastic, chemical, printing, and electrical equipment fields. Where any type of manufacturer or power company employs electricity or runs motorized equipment, thermography could be an indispensable form of predictive maintenance. Although nuclear power plants and large-scale factories have been the earliest to use thermography, virtually all other factories could implement IR techniques as well. The two factors limiting widespread use of thermography in PM are sophistication of imaging technology, and costs of implementing an IR-based predictive maintenance regime. We discuss these factors below.

Market Analysis. Engineers at industrial plants, fossil fuel power plants, factories, and nuclear power generator plants choose thermography as touchstones of their PM regime because it saves them money by avoiding lost production and downtime from costly electrical or mechanical failures. Anheuser-Busch, for example, used to thermally inspect three days a year with outside consultants from the American Risk Management Corporation, but now inspects for three full weeks every year.

The nuclear power industry, in particular, leads the way in implementing IR thermography in predictive maintenance regimes. Careful planning and design for fail-safe operation are absolute industry requirements, because of the obvious public and government concerns. Regulatory agencies like the Nuclear Regulatory Commission (NRC) set the absoulute highest maintenance standards of any industry. From the nuclear plant operator's point of view, a single day off-line could cost an average plant $750,000 in lost time, lost power generation, and restart man-hours, so even the remote chance of component failure, major or minor, is avoided. The Southern Nuclear Operating Company, which leads the nuclear industry in sophisticated thermography, surveys 3,409 different components yearly.[41]

One of the most cost-sensitive surveys that has been developed by nuclear power generators, for example, is the quarterly inspection of condensers for air in-leakage. Another is routine inspection of feedwater heaters in boiling-water reactors, which minimizes wasted steam due to leakage. These have direct benefits to plant and consumer alike, according to officials at Southern Nuclear, and by reviewing the results, plant personnel can prioritize future maintenance and save further time and money. Southern Nuclear's thermographers identified, in 1991 alone, an overheated terminal board connection in a rod control cabinet which saved them $200,000. They also located condenser air in-leakage points, high resistance in bus connections, and leaking feedwater heater shell relief valves.

The cost benefits of utilizing thermography for PM are increasing, moreover, because many insurance companies since the mid-1980s have reduced premiums on facilities using thermography. One of the strongest voices for reduction of premiums for companies using thermography is the Cleveland-based American Risk Management Corporation (ARM). They provide guidelines for the insurability of industrial plant and power-generating facilities, especially in the nuclear energy industry. Not only do they reduce premiums on clients using thermography, but they provide thermographic consulting services to industrial plants, fossil power facilities, and nuclear power plants, and help facilities select the right thermographic equipment. A predictive maintenance engineer at a large nuclear power plant we contacted said that he had saved enough cash in three years of reduced insurance premiums to pay for his five diagnostic IR imagers, which cost about $100,000 a piece.

Within three to five years, insurance companies officials claim that virtually all factories and power generating companies will have reduced premiums when they use thermography, which could pay for the cost of even expensive IR systems. This will be a tremendous boon to the IR thermography industry. But insurance company coverage will follow only after three criteria are first met, according to industry executives: electrical and mechanical groups must approve thermographic standards on equipment, operators must be formally certified in

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[41] See N.A. MacNamara and A.E. Hammett, "Development of a Comprehensive IR Inspection Program at a Large Commercial Nuclear Utility," Thermosense XIV (SPIE: April 1992) pp. 30-41.

accordance with universal standards and share an approved, universal body of knowledge, and industrial trade groups must formally endorse and require thermographic inspections of their member companies.

It may take three to five years before all these prerequisites are met. First, thermal signature standards have not been fully established yet for many electrical and mechanical components. For example, the American Society of Mechanical Engineers (ASME) has Boiler and Pressure Vessel Code requirements for thickness measurements, material and weld inspections, but no code requirements for infrared inspections. Thermographers have pressured manufacturers of motor and electrical components to issue standard thermal profiles for their products, but this would be a dramatic and costly step which is unlikely.

The bulk of necessary research on mean and abnormal operating temperatures of components has already been conducted by the three leading industrial standard-bearers: ANSI, IEEE, and NEMA. According to insurance executives we contacted, this is sufficient. For years, themographers have used those societies' "delta-T" temperature ratings to assess the severity of overheating electrical components. There are temperature standards for electrical components ranging from circuit breakers to switchgear to air switches, insulators, and bus supports. For any piece of standard equipment, these societies have issued joint standards on preferred ambient operating temperatures, on optimum temperature rise above ambient for operating components, and total temperature for the component operating at room temperature, as illustrated in table three below.

**Table 3. Sample Electrical Components and Safe Temperature Rises**

| Equipment | Component | Ambient | Rise | Total |
|---|---|---|---|---|
| Cable Insulation, Thermoplastic[42] | All Polyethylene | 30 | 45 | 75 |
| Low Voltage Circuit Breaker[43] | Terminal Connection to Buss (or cable) | 40 | 55 | 95 |

Certification of PM engineers is also becoming a reality. Major trade societies are stepping in to certify IR inspectors. Several independent societies have certified users since the 1980s, most notably the Infraspection Institute in Shelburne, VT. Two major firms, Dow Chemical and McDonnell Douglas, have been instrumental in organizing a thermographic

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[42] ANSI IEE Standard 242-1986 IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial power Systems.

[43] ANSI/IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

certification program since about 1989. A major breakthrough in 1992 was approval by the American Society for Non-Destructive Testing (ASNT), the oldest organization of its kind in the country, for Level I and Level II certification for thermographers. Level III qualifications are set to be approved in 1993. Since the ASNT is the most credible certification organization in the country for non-destructive testing, this virtually ensures thermography's future.

The last criterion to be met will be requirements by leading trade societies that member companies thermally inspect their mechanical and electrical equipment. For example, the National Fire Protection Association (NFPA) recommends annual infrared inspection of electrical equipment as well as an initial inspection for newly installed equipment, but it is reluctant to *require* it. This is because thermography still suffers from a credibility gap created in the 1970s and early 1980s. During the early days of thermography, imprecise vidicon cameras with sensitivities no better than .5 °C, using monochromatic cameras, offered very poor resolution but were touted as valuable PM tools. They did not deliver on their promise, undermining the PM community's support. Additionally, the new MCT- and InSb- based radiometric thermography cameras can demonstrate hot and cold spots on equipment so dramatically that many consultants are not subjecting users to training and certification. Their work is often shoddy or outright fraudulent, according to marketing executives at the major IR thermography firms. This too will have to change before insurers sweeten economic incentives by reducing premiums on engineers using thermography in their plants.

If insurers do reduce premiums for plants and factories using thermography in PM, the price of IR machinery will largely determine their market potential. We estimate that about 15,000 vidicon cameras have been sold during the past ten years, at about $15,000 to $25,000 per unit. The mean price is just over $20,000. Vidicon camera systems are comprised of a camera, several lenses, a video cassette recorder, and accessories like a battery pack. Since they come without expensive analytical hardware and software, they appeal to smaller companies with mechanical and electrical equipment. Unfortunately, most users report that the equipment is not helpful in truly predictive inspection, which is the domain of more expensive and sophisticated IR systems.

We estimate that about 10,000 sophisticated IR cameras and workstations have been sold in the past ten years. Their prices range from $65,000 for single point photoconductive scanning systems to $185,000 for staring units. The mean price is about $80,000. That includes the portable camera, video or data storage equipment, and extensive PC-based computer hardware to process data, storage capabilities up to about 80 megabytes, and comprehensive analytical software.

The consensus among company executives and trade officials we contacted was that sophisticated IR systems using focal plane arrays, with radiometric ability, will find a substantial market so long as unit costs remain, on average, under $100,000. The market is just beginning to open up for radiometric instruments which are sensitive (NETD <.1°C) and present live data (>60HZ). At this point, currently available scanning units do this painstakingly and at high expense because they must sacrifice sensitivity for scan speed, and vice-versa.

The two types of customers most likely to purchase the first high-end staring IR instruments are factories or power plants with either high insurance rates, or large numbers or repeating machines and electrical components. Since utilities, most notably nuclear power plants, and petrochemical firms are almost universally large facilities with hundreds of pieces of identical machinery, they would be prime customers. Within five to seven years, the market for IR detectors could radiate down into smaller factories, in the chemical, plastics, metal, printing, and processing industries in line with cost reductions in IR systems. Most of the radiometric market could be reached, according to IR company executives, if workstations were about $75,000. Staring, radiometric IR systems are <u>not</u> likely to compete for the lower-end of the market for qualitative thermography, which will likely stay with vidicon cameras. But staring cameras could dominate all quantitative applications where trending would be simplified and more precise.

People we interviewed made it clear that staring IR cameras with radiometric qualities would revolutionize the predictive maintenance market. They would vastly improve trending features of PM, with improved sensitivity and real-time imaging. They would heighten and solidify interest in thermography as a PM technique among trade societies, certifying bodies, and insurance companies. We estimate, based on interviews with companies which thermally inspect factories, and with commercial IR system producers, that over 15,000 units a year could be sold of high-end radiometric systems beginning in the next three to five years. At a conservative $80,000 price per unit, the IR thermography market could be valued at $1.2 billion per year. Later on, sales could expand to about 20,000 to 25,000 a year once insurance firms reduce premiums for companies using thermography and prices fall in thermal inspection systems. Even presuming that unit prices also would fall during that period, the market value could easily reach $1.5 billion/ year.

MCT-based IR detectors are well placed to lead the commercial market in thermography equipment. All the major companies producing IR equipment for predictive maintenance -- Amber Engineering, FLIR Systems, Inframetrics, and AGEMA -- supply either InSb or MCT scanning detector systems. Salesmen at all those firms say they would vastly prefer MCT-based detectors because its higher sensitivity is required in PM applications, and because it can image over the entire infrared spectrum (2-12 microns) instead of being limited to the MWIR like InSb-based detectors. Executives whom we interviewed also indicated they believe MCT-based mosaic arrays on CZT substrates to be superior to InSb-based ones, and would be eager to integrate such arrays into their products if prices were lower.

The LWIR has generally been used by IR thermographers in predictive maintenance, but

InSb-based systems in the MWIR are also common. Although the 8-12 micron band has a higher radiance and higher thermal derivative, the 3 to 5 micron band offers higher contrast to thermographers doing PM. Traditional imaging systems have shown limited performance characteristics in the 3-5 micron band due to the low radiance, particularly at low background temperatures. But recent advances in 3-5 micron detector technology have overcome these limitations, according to system designers we contacted. One of the predominant factors that affected band and detector selection was the lack of read-out performance at the lower photon-radiance levels of MWIR detectors. But new, higher quantum-efficiency staring array sensors in the MWIR overcome the low band radiance limitations. The higher image contrast in the MWIR, higher operating temperatures, and low-cost MWIR staring sensors make that band more attractive than ever.[44] We believe the MWIR will be favored over the long-term since MCT-based staring detectors can operate in the MWIR at warmer temperatures and still deliver better performance than scanning systems.

Detector and System Design. Most current models share certain features. Machines usually measure temperature from -20°C to 400°C (-4°F to 752°F); the most extended range is about 20 to 1500°C (68 to 2732°F). The horizontal field of view (HFOW) is usually about 20°, and the vertical field of view (VFOV) is 15°. Systems generally focus from about 4.7" (12cm) to about 2 kilometers.

But as suggested previously, there are four specific trends in the design and features of thermal imaging equipment for predictive maintenance. First, staring detectors, specifically in the MWIR, will be integrated increasingly into sophisticated PM systems. This will allow constant image acquisition with high precision.

Second, radiometric systems will overtake all qualitative equipment if prices can fall below $100,000 for a complete system. This will allow better trending and more failsafe predictive maintenance, so it is extremely desirable for large factories and utilities. Sensitivity should be slightly under .1°C. A few systems, specifically Amber's InSb-based AE-426 system and Inframetric's Model 760, claim to resolve below .1°C, but most operators state that in real field operations, .1°C was the best they could get.

Third, systems need to be lightweight (under 25 pounds), rugged, portable, and use little power so they can operate on rechargeable batteries. Only the camera and video/data recorder need to be portable, since in most cases the analytical hardware is kept in remote workstations.

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[44] J.T. Woolaway, "New Sensor Technology for the 3-to-5 micron Imaging Band" Photonics Spectra (February 1991) pp. 113-119.

Fourth, software is the diacritical factor for adapting IR detectors to the predictive maintenance market. The unexcelled leader in software integration for predictive maintenance is Inframetrics with its ThermaGram software package, according to users we contacted. ThermaGram software allows complex algorithms, analyses, and display modes to work on ordinary IBM-compatible PCs. The user can compare multiple images, track and measure high-speed thermal transients, see a thermal gradient, perform statistical analyses of temperatures, and dynamically subtract part of an image from the rest. Images can be viewed in 3-D. Users can freeze any portion of an image while maintaining dynamic imaging throughout the remainder of the display. Users can display multiple images in a quadrant for simple visual comparisons, while the program compensates for different images recorded at differing ranges. Thermal or visual images may be transferred from a floppy disk, VCT, VDR or still camera. All or part of an image may be magnified for fine detail. Images can be viewed in black and white or 128 colors including ten pre-defined palettes. ThermaGram can display absolute temperatures in any points in an image, highlight regions of equal temperature (isothermic analysis), provide smoothing and edge enhancement on thermal patterns, make histograms of temperatures of area of interest, and plot during inspections time vs. temperature in up to three areas simultaneously.

Several add-on software modules can expand trending analysis with more graphs, perform pixel by pixel emittance correction and eliminate the effect of non-uniform background radiation on stationary objects, and conduct complex data storage and retrieval tasks. If staring IR detectors expand the complexity and precision of data collection during PM surveys, then advanced software is required to harness that power.

Suppliers. A relatively small number of suppliers have provided the 25,000 IR systems sold for predictive maintenance in the past decade.

- **AGEMA Infrared Systems,** based in Danderyd, Sweden, is sold in the US by Eklund Infrared in Verona, N.J. Its line of Thermovision cameras is the most expensive on the market ($60,000 to $185,000), and is more frequently used in the non-destructive testing and research communities where system cost is less of an issue because companies only need to buy one or two units. Agema's Thermovision 900 Series is comprised of three all-digital LWIR and MWIR scanning detectors which maintain measurement accuracy of 1 percent and repeatability of .5 percent regardless of the ambient environment. The 970SW version, for $99,500, uses a two-bar SPRITE detector which is TEC cooled. The 900SW version uses a two element InSb array, and costs $117,975. The 900LW uses a single MCT detector and is also $117,975. Stirling closed-cycle coolers are optional on those systems; open cycle coolers are standard. The ERIKA software has full data analysis capabilities, such as isotherms, spotmeters, histograms, and profiles. It uses a Windows-style environment to manipulate and crop images.

The AGEMA Thermovision 800 BRUT series is somewhat cheaper. The microprocessor controlled measurement system provides +-2 percent or +-2 percent accuracy. Systems range in price from $59,950 for the Systems 487 & 488, to $69,950 for the System 489, to $83,500 for System 897SW, 898SW, and 898LW.

AGEMA's absolute top-of-the-line model, the Magnus Dual Brut System, is priced at $185,000. It has a 105 MByte hard drive, and a TEC-cooled SPRITE detector, which is an efficient scanning system with built-in scanned micro-blackbody temperature references in a microprocessor controlled, rugged, drop and vibration tested scanner unit. AGEMA claims sensitivity is better than 0.1°C. Accuracy is better than +-2 percent or 2°C. Altogether, we estimate that AGEMA accounts for about twenty percent of the infrared PM market.

• **Inframetrics,** in North Billerica, Massachussets, is the acknowledged leader in IR detector systems for predictive maintenance. We predict that the company has over 35 percent of the market for IR systems for PM. All Inframetric's systems are desktop, but can become portable with a carrying harness. They all have an LCD color screen, extensive software features, and the best features (zoom, crop, focus to maximize contrast) of the systems on the market. Model 600L is Inframetric's standard portable unit for PM, using a single MCT-based detector operating in LWIR (with dual MWIR-LWIR optional), cryocooled. A MWIR version is available, which is also cryocooled. The unit sells for $75,000. It offers standard TV output with the fastest scan rate commercially available (60Hz vertical scan), and is sensitive to 0.1°C. The Inframetrics Model 740 sells for $85,000, and integrates Inframetric's patented electrical microcooler. All Inframetrics systems come with versions of their ThermaGram software, which is the best available according to most thermographers.

• **Amber**, in Goleta, CA, supplies both the military and commercial markets with IR detector related equipment. We estimate that the company has about 25 percent of the predictive maintenance market. Its AE-4256 IR camera system uses a staring 256 X 256 InSb matrix with 38 micron pitch. InSb detectors are hybridized onto a CMOS multiplexer by selective indium deposition and room-temperature welding bonds. A support electronics unit also calibrates the unit, and non-uniformity coefficients for gain and offset are stored for each of the 65,536 pixels in battery-backed RAM. Variable frame times up to 60 Hz make this, alongside Inframetrics' systems, the fastest unit available. The system is cryocooled to liquid nitrogen temperature. The system costs just under $100,000.

Amber-View software allows real-time image processing and analysis. It combines camera control, image processing and display, and a wide array of tools for mathematical and graphic analysis in a single Window's style program. It operates similar to Inframetrics' ThermaGram, but lacks many of •'.. trending and histogram functions because its emphasis is on graphic presentation.

• **FLIR Systems**, in Portland, Oregon, was a subsidiary of Hughes Aircraft until 1991 when it became independent. Its IR systems are popular in predictive maintenance, non-destructive testing, process monitoring, and remote sensing. The IQ Series Model 325, at $55,000, uses a single-point scanning MCT-based detector which is TEC-cooled. It uses a 32-bit CPU and internal hard drive and the TIA Power-Analysis software. The IQ Series Model 812 operates in the LWIR, and uses an open cryocooler. FLIR claims Model 812 is sensitive to 0.06°C, but users said they got not better than 0.1°C. It is also MCT-based, but uses a 30 X 1 scanning array.

The Probeye 7300, FLIR System's top-of-the-line model, costs $65,000. It uses a 30 X 1 scanning MCT array with a solid-state Peltier electric cooler. Like most systems, its top resolution is 480 X 512 pixels. Its scan rate is 30 frames per second. The main drawback to FLIR Systems' thermal imagers is their software. AGEMA, Amber, and Inframetrics have developed extensive analytical software for the predictive maintenance market, but FLIR has not. Until the company develops better software, it will be restricted to less than ten percent of the market.

Aside from these manufacturers, a myriad of consulting firms conduct infrared inspections for predictive maintenance, and affect the development of products because they are the manufacturers' prime customers. Prominent among them are the **American Risk Management Corporation** in West Brookfield, Massachusetts, **Electric Power Research Institute** in Eddystone PA, **John Snell & Assocs.** in Montpelier, Vermont, **Infrared Research Inc.** in Rossville, Georgia, **Baird Infrared Technology Inc.** in Wilmington, Delaware, and **Entech Engineering** in St. Louis, Missouri.

## Process Control

Process Control is an area of application for sophisticated infrared detectors with exceptional promise and scanty current use. Infrared detectors were introduced into the process control market only three to four years ago, and researchers have steadily uncovered a number of new, substantial applications which ensure their future. Although much of the research into infrared detectors is still in its infancy, we project an annual market totaling $560 million annually within five years. More than any other field of application for IR detectors, the process control sector offers a ground-floor opportunity for manufacturers of advanced infrared detectors to nurture a new application and thereby help create a new market from the beginning. Individuals who were interviewed for this section are listed in Appendix K.

In process control, sensors are used to monitor the industrial outputs of manufacturing and assembly lines, testing for quality within preset tolerances. Infrared detectors are one new tool in a larger set used by engineers for process control. The introduction of microprocessors has increased significantly the instruments available for process control. Traditional tools of process control have included pressure transducers, thermocouples, weight scales, and micrometers. Newcomers include ultrasonic sensors, Hall-effect transducers, and encoders. Although quality control engineers will make use of all these tools, machine vision is far and above the leading new technology which is revolutionizing process control. And infrared sensors could command a significant segment of these emerging machine vision applications.

Machine vision, as a form of process control, creates an electronic image of the manufacturing product which is then analyzed by a microprocessor. The analysis compares measured geometric and mathematical values against predetermined tolerances. The differences represent errors in the manufacturing process, and provide a basis for implementing a control strategy to modify the source of the error, if significant. A machine vision system comprises a digital camera, an illumination source (which is omitted in many cases of IR inspections, as explained below), a processing computer, and sophisticated software to carry out the analysis and provide feed-back to automatically modify the manufacturing process.

The most straightforward consequence of a machine vision control system is to withdraw a defective product from the manufacturing process before any more value is added to it. Signals from the vision system, in either digital or analog form, discriminate between qualifying and non-qualifying products. Faulty parts can then be automatically discarded before they are shipped. For example, shelled pecans and walnuts can be inspected to identify shell fragments that remain. A solenoid can be activated upon recognizing a shell, releasing a burst of air onto the conveyer belt which blows the shell into a "reject" receptacle.

Alternatively, sophisticated machine vision systems could be placed at several steps along the production process, to identify defects as early as possible, and provide input into a feedback loop which readjusts machinery to undo the cause of the defects. Although this is the eventual aim of machine vision regimes, nearly all IR systems used currently in process control do not offer feedback into the production process. Although quality control engineers may use infrared imagers to locate the exact point in an assembly line where defective products originate, servo-style feedback loops, which would automatically modify the production process to minimize defects, are still several years off.

In the following sections, we discuss some of the specific applications potentially available for sophisticated infrared detectors, and discuss requirements to adapt military-style IR detectors for this process control market. In the market analysis section, we estimate the potential market for infrared process control equipment, and assess the potential for MCT-based IR detectors to benefit from that market.

Applications. Infrared imaging is likely to constitute a significant sector of the emerging machine vision market. Since the application of IR detectors to process control is relatively new, we describe their potential in two manners: first, by enumerating the strengths which IR offers, suggesting several areas into which detectors could potentially migrate (but are not yet) and secondly, by describing current applications which have already flourished or are being actively explored.

IR detectors offer six advantages for machine vision applications. First, IR detectors, especially in the LWIR, can see through mist, dirt, and vapor on the factory floor. Mist is used often as a coolant and can intrude on the optical path of traditional imaging systems, resulting in signal attenuation and image distortion. With web-produced metals and injection molding, in particular, steam and mist are present during almost all stages of production, making conventional CCD cameras, which operate in visible light, ineffective.

Second, IR detectors perform well with self-luminous objects, such as hot or cooling objects, which emit natural IR energy. IR energy can be monitored to assess the rate and uniformity of cooling or heating of an object, without the need for outside illumination. This is not possible with conventional CCD cameras operating in visible light.

Third, IR detectors outperform CCDs in visible wavelengths where the objects being imaged are translucent or transparent. This applies to transparent coatings and laminates, clear and colored glass such as bottles, windows, optical lenses, television screens, and plastics. Even with opaque glass or laminates, added dyes become translucent after about one micron, so IR detectors can see through them.

Fourth, as the gist of automated inspection is to locate specific wavelengths at which contrast is maximized between defective and normal products, the infrared greatly broadens the wavelengths available to researchers, and is particularly valuable. Even with the minimal efforts undertaken so far to explore IR for automated inspection, certain contrast points have been located which distinguish nuts from shells, bruised or rotten fruit and vegetables from normally ripe produce, burnt food from adequately cooked products, and rotten grain from normal, using IR wavelengths. Most machine vision integrators we contacted stated that they would consider IR wavelengths whenever seeking contrast points for automated inspection, if cameras which suited their needs were available.

Fifth, materials which are reflective, and therefore hard to illuminate, could benefit from infrared inspection. For instance, the process of finding defects in web sheets of metals is difficult with machine vision systems which operate in visible light, because the metal reflects most of the light. By comparison, IR detectors could image the object either in conjunction with infrared illumination (which is still reflected somewhat by metals), or, preferably, by passively sensing heat given off by the sheet metal.

Sixth, IR detectors can perform another function completely unavailable to visible-light CCD prevalent in the machine vision marketplace: they could monitor objects as they cool down, or heat up. This could be invaluable to manufacturers and shapers of metals, fabrics, rubber, plastic, and paper, not to mention chemical manufacturers, semiconductor manufacturers, and purveyors of injection molded plastic or metals, and automated welding manufacturers.

Seventh, IR illumination does not damage photosensitive materials, such as camera film, which would be damaged by visible light. IR detectors are therefore an option, competitive with UV, for process control in the production of photosensitive materials. Although no applications whatsoever have been explored in this area, to our knowledge, it is nonetheless open to IR detectors.

These strengths of IR detectors have led already to their development for several pilot applications. Although IR is far from reaching its potential in process control, there are a slew of applications under investigation. Most applications are closely held by their developers because the process could have a significant effect on profit margins by minimizing the cost of faulty products, or by maximizing chemical processes as well as cooling and heating of products like metals, plastics, rubber, etc. Almost all the companies we contacted, whether IR camera integrators or factory-floor users, played their cards close to their vests -- more so than was the case with other application sectors. The current applications we describe below fall into two general categories: machine guidance, and automated inspection.

Machine Guidance. Machine guidance refers to robotic assembly, where machine vision guides servo-driven machines in the process of fabricating a product. In this type of application, vision algorithms operating on images transmitted from a camera mounted on a robotic arm determine the location and orientation of objects and parts being manipulated during assembly. Specific examples of machine-guidance applications include component pick-and-place in electronics, windshield placement in automobile manufacture, semiconductor wafer alignment, and integrated-circuit wire bonding. Each of these applications depends on machine vision for automation of an assembly process.

Every integrator we contacted expressed a strong interest in experimenting with infrared imagers for machine guidance, but stated that systems are not widely available, and too expensive. It is unclear whether this is due to a lack of contact between commercial IR camera manufacturers and process control integrators, or due to the high cost of conventional IR cameras (over $50,000). Integrators stated that since objects, especially when hot, have unique thermal signatures, infrared detectors may pick up contrasts and shades which are not possible with visible light cameras for machine vision.

Weld Control. The most developed application which uses infrared contrast points is weld control. Although all indications are that automated welding systems could become pervasive in manufacturing, systems have so far been developed only for specialty weld processes, such as gas metal and gas tungsten arc welding. Typically, these systems have been designed for special applications, such as welding inaccessible areas of ship hulls, missile trajectory-control vanes, or to repair highly radioactive fusion reactor components, where it would be dangerous or too expensive for humans to weld.

More down to earth, IR detectors can be used in dynamic applications for either spot welding, arc welding, or line welding. Adaptive welding, using IR detectors, is the key to success in the implementation of all these robotic welding systems. Quality of the weld produced by the robotic welding system depends primarily on accurate positioning of the weld pool and controlling its penetration depth. In manual welding, the welder ensures the quality of the weld by monitoring and manipulating the process parameters according to the changing environment. In automated welding, the same perception and judgment must be exercised by the sensor, microprocessor, and software.

For example, an IR-based imaging system is in use by an air bag manufacturer to monitor the welding of an electrical switch, and has reduced reject rates to below five percent in addition to eliminating the possibility of an undetected, faulty switch slipping through. A second, real-time, in-line inspection use, also involving electrical components, involves the high-speed soldering of contacts used in telephones. Here, a silver-cadmium-oxide electrical contact is being attached to a beryllium copper strip at a rate in excess of 600 solder joints a minute. As a YAG laser beam solders, an IR camera compares their thermal signatures with pre-programmed norms.

For now, these IR systems accept or reject solders and welds in accordance with statistical comparisons. Eventually, integrators could close the loop in a servo-style manufacturing environment, and have a completely adaptive control system where the computer will make the required adjustments to process variables itself, in real time.

Several types of sensors have been explored since the 1960s in order to automate weldings, but the complicated environment lends itself well to IR imaging. Some of the more common, and older sensor types include optical CCD cameras, photo-diodes, acoustic emission sensors, ultrasonic sensors, tactile sensors, and finally, infrared sensors. Optical CCD cameras are the most commonly used. These cameras have been used for different purposes such as determining weld pool contours, open loop control of the welding process, pressure vessel reading, guiding automated roving vehicles, real time control of robots and for guiding electrodes.

However, infrared detectors offer several advantages over these traditional methods of weld control. First and foremost, they allow monitoring of several variables simultaneously. Front-side infrared sensors can provide information about both weld penetration and bead width, whereas traditional systems can only inspect for bead width control. Weld joint penetration control, in particular, is the key to producing reliable and consistent automated welds, and only IR detectors image it well. There are two distinct methods of weld joint penetration control depending upon the thickness of the plates being welded. The first, and simpler method, is to maintain a fixed penetration depth in a plate of constant thickness. The second, and more difficult method, is to maintain a constant weld penetration depth in a plate with varying thickness. IR detectors have been found useful in both varieties of weld penetration control.

There are, however, two significant problems in integrating IR detectors into automated weld inspection systems. First, research is still at an early phase; although several firms specializing in machine vision integration, which we contacted, were interested in fielding such machines, it could be about five years until operational systems become available. Second, and more importantly, several experts outside the automated welding research community indicated that researchers had overlooked the fact that a spot being welded changes in both temperature and emissivity; this makes it difficult to read absolute temperatures. Although a multi-band inspection system could overcome this problem, no researchers are currently experimenting with one.

In all, weld control is a promising application, especially if automobile manufacturers become interested. Although more research needs to be conducted, weld control has proven itself in specialty applications and is several steps away from becoming mainstream. It is a promising, albeit long-term application for IR detectors.

Automated Inspection. Automated inspection refers to automatic defect detection, where a vision system is used to find flaws in manufactured goods, early-on in production, before additional costs are incurred manufacturing a product that cannot be sold. In these types of applications, inspection algorithms using image-processing principles are employed to determine the location and orientation of objects under inspection, as well as to detect and map any defects found during inspection. Specific examples of such applications include semiconductor-wafers, paint-lines, and food inspection. Each of these applications, described below, uses vision as a means to increase production throughput, as well as to ensure product quality. It is in this field that most near-term IR applications lie.

One of the most demanding and potentially pervasive applications for infrared detectors in automated inspection is in web inspection. A "web" is a continuous strip of material emerging from a production process. By inspecting webs of material, manufacturers can detect voids, inclusions, and surface defects, which are revealed by variations in background radiant flux, and emissivity. In addition to ensuring product quality, web inspection is necessary to detect faulty parts of a continuous sheet which could cause rips in the line, cause entanglements, damage the web machinery, or otherwise cause shut-down.

Specifically, the metal, textile, plastics, and paper industries produce virtually all their materials in webs. While factors such as size, shape, location, orientation, or registration of repetitive patterns or colors in some web processes need only be verified occasionally, key forms such as steel, aluminum, and similar metals require continuous inspections.

Aluminum manufacturers, for instance, have pioneered the application of IR detectors in the inspection of webs. High quality aluminum, which is used to manufacture beverage cans, needs to be free from flaws which may damage the die responsible for forming the can, and also free from cosmetic flaws such as dirt streaks, stains, or other discolorations. Since every manufacturing step adds cost to the aluminum sheet, and since sheets with even minor defects need to be discarded, continuous web inspection to detect such defects early-on is extremely valuable to manufacturers.

However, the manufacturing environment for aluminum, and metals in general, is too demanding for conventional imaging systems. Sheets as wide as 80 inches exit from a hot rolling mill at an average speed of about 1,000 ft/min. The sheet is usually warmer than 500°C. A mist is continually sprayed to act as coolant and lubricant. Mill vibration can be significant. Moreover, the imager needs to be stationed at least six feet away from the web to reduce the chance of damage to the system if the web rips and backs-up, and the system needs to run 24 hours a day, all year long, with minimal maintenance.

Conventional CCD cameras which operate in visible light have failed at this application for three reasons. First, mist from the coolant/lubricant obscures the line of sight necessary for optical imagers. Second, illumination, which is necessary for inspection by visible light CCDs, is difficult both because of mill vibration, which causes a lot of shifting shadows and bright spots, and because aluminum is highly reflective, with an emissivity below about 0.1. Third, external illumination naturally adds another high-maintenance component to the inspection system.

Even though IR detectors overcome all three hurdles and thus offer overwhelming advantages over conventional CCD cameras, they need high resolution, accuracy, and speed to succeed at web inspection. Table four below summarizes the parameters for a typical inspection system for an aluminum manufacturing plant:

**Table 4. Parameters for Inspection of an Aluminum Web**

| Parameter | Measurement |
|---|---|
| Crossweb resolution | 0.125" |
| Downweb resolution | 0.125" |
| Angular resolution (across and down) | 1.3 mrad |
| Width of sheet | <80" |
| Minimum perpendicular standoff | 72" |
| Field of view | 60° |
| Depth of focus | 12.4" |
| Sheet speed | ~1000 ft/min<br>(200 in/sec) |
| Line scan rate | 1600 lines/sec |
| Pixel rate | ~1.23 M pixels/sec |
| Target temperature | 500°C |
| Target emissivity | ~0.07 |
| Sensitivity threshold modulation | 15 percent |

Overall, this is an extremely demanding application. The fast throughput in web production lines is among the quickest IR detectors could encounter. Certain parameters stand out: a necessary resolution of 0.125"X0.125" from about six feet away, a line scan rate of 1600 lines/sec, and a scan rate of about 1.23 Mhz.

Other industries pose less demanding requirements and are beginning to implement IR systems in their web production lines. Selenise, a large multinational textile company in Shelly, North Carolina, for example, has cut its rate of fabric rejection from seven percent to under two percent by adding MCT-based IR detectors in two locations in each web line. As with many other companies, Selenise uses IR machine vision also to assess improvements or monitor changes in their production methods, in additional to quality control.

Another large market for web-style inspection lies in the manufacturing of printing paper. The methods being developed are being held closely by paper mills. In this application, line scanners based on either InSb or MCT determine the moisture content of a printing paper web as it emerges from a hot production mill. The term "web" originated in the paper mill industry, where a woven web of paper fibers is moved through a pool of liquid paper fibers, and slowly collects a film of paper. IR detectors sense the latent heat in the paper, which increases in proportion to the paper's moisture content. Paper with a high moisture content would require either more heating (to dry it out), or be discarded before it warps, rendering the entire roll unsellable, or cause the web to break and damage machinery.

Line scanners can be integrated into several spots in paper production lines which are likely to cause high moisture content. For instance, excess moisture arises frequently at the "wet end" where the paper goes from less than 1 percent solid to more than 20 percent, and also at the presses, where the sheet exits at 40 percent solid, and finally in the dryer section, where the sheet is dried to about 95 percent solid. Several industry leaders, such as Champion paper, Scott pap and S.D. Warren are said to operate several IR line detectors on each web production line at these points. But line scanners have become increasingly valuable to paper mills, and even more so now that new "yankee" dryers are becoming prevalent. In yankee dryer cylinders, paper is steamed to 270°C at 150 psi in a 20 foot-wide, 18-foot diameter chamber, at speeds between 5,000 and 7,000 feet per minute. Condensate from the interior surface often remains on the paper, and can cause serious mechanical problems if it backs up or warps the web of paper.

Another web-like application for the detection of voids, inclusions, or cosmetic defects is in glass manufacturing. As glass cools after being molded into bottles, jars, glasses, windows, etc., it releases heat which fluctuates in accordance with its uniformity. Thinner or cracked areas would emit less heat. Almost any wavelength beyond about one micron can reveal defects in glass material, whether transparent or dyed, according to experts. In this application, thermal inspection would lead to the removal of defective bottles to avoid adding more manufacturing costs. A leader in this application is the Coors Brewing Company, which not only has an extensive thermal predictive maintenance regime, but thermally inspects its bottles (and cans) before filling them with beer.

Finally, future application of IR detectors in web inspection will go well beyond the materials listed above. Food harvesting, grading, and packing are all web-like functions awaiting the development of robust machine vision capabilities similar to ones employed in metallurgy. The inspection of streets and highway awaits an automated web-like inspection system. For example, California Transit (CalTrans) requires inspection at 55 miles per hour, for cracks in concrete as narrow as 1/8". As with other web inspection systems, manual methods of inspection are costly, time consuming, and largely inaccurate, and IR thermographt has been a proposed solution.

Another potential process control application which could employ IR detectors, the monitoring and control of virtually any chemical reaction, is closely held by chemical firms. Generally, chemical reactions either give off heat or, less frequently, absorb heat as they progress; these are called either exothermic or endothermic reactions. Heat usually follows a unique bell curve for each chemical reaction, peaking after some time and tapering off when molecular reactions are completed. If the chemical reaction could either be maximized to take less time, or be tuned so that all the reactants mingle, yield and throughput would increase, as would profits. It is therefore beneficial to monitor the profile of chemical reactors while large reactions take place, either to simply follow the process of molecular formation, or to modify the temperature and concentration of reactants to maximize yield. Dow Chemical is said to be the absolute research leader in this field. Likewise, petrochemical firms are said to be heavily invested in trying to apply IR detectors to the refining of oil.

According to industrial firms we contacted, no systems have been fully integrated yet, but the potential applications in chemical and pharmaceutical industries are tremendous. Any chemical reaction which involves heat (ie. nearly every one) could be fine-tuned or expedited by placing IR detectors in open process control loops at several steps in the chemical process to monitor temperature distribution. Alternatively, new chemical processes and manufacturing equipment could be examined for their temperature profiles and modifications made to maximize yield.

Another potential application is the monitoring of products or inputs as they either cool or warm. In this application, IR detectors would follow the change in temperature over the entire surface of a product, testing for uniformity and preferred rates of cooling or heating across the entire surface. This has never been done effectively previously by other methods. In rigid injection molding of all sorts of plastic or metal products. For example, infrared detectors could monitor the mold from the outside to ensure that all areas had been filled with molten material and are cooling adequately. In the plastics industry, especially, where injection molding predominates, voids or flaws show up clearly in the thermal signature of products after the mold has been broken and the product is cooling. Ford is said to have used this technique experimentally during the 1980s on the production of car bumpers. After assessing the bumpers thermally during production, Ford reportedly located the root of the production problem, refined the equipment, and did away with thermal inspection.

With injection molded metal products, on the other hand, where voids or flaws are less common, IR detectors could monitor the cooling rate of stamped/molded products to detect when the products had cooled enough to advance to the next production step. Heat treated metal products, such as car gears, could be monitored thermally to ensure that the entire surface reaches certain temperatures, and is therefore tempered. Small areas on tempered gears could also be monitored thermally as they cool, to ensure that some parts do not cool faster, causing the gear to warp.

Within the semiconductor industry, the use of IR detectors has been researched extensively, and in some cases integrated already in production processes, to monitor the rate at which wafers cool. Temperature stability across a wafer, and an exact cooling rate, create the best conditions to ensure wafer uniformity and shape. This is true for both inexpensive wafers for integrated circuits, and state-of-the-art wafers for IR detector circuitry. Motorola's Semiconductor Assembly Manufacturing plant has pioneered the use of IR detectors to detect the temperature profile of cooling wafers in a process control application which feeds back into a computer to adjust the concentration of reactants and regulates production chamber temperature.

Another process control application which potentially could use IR detectors, is monitoring tool wear during manufacturing. Companies lose a significant amount of money each year from scrapping machined parts which are defective as a result of being cut by worn tools. Researchers have found that tool wear is readily detectable by the increased heat generated during use. By focusing at the chip side of cutter interfaces, or on the tool bit itself, for example, researchers have suggested that IR detectors could be used to monitor tool wear to avoid overuse of worn tools that produce out-of-spec products in virtually any industry.

Finally, food inspection could benefit from IR detectors. Although very few food inspection researchers have explored the application of IR detectors, several uses have already emerged. Using IR illumination and an IR camera filtered to specific contrast-point wavelengths, several companies have begun sorting shells from nuts in an assembly line, for example, using wavelengths in the MWIR. Post Cereal is reportedly using monochromatic IR detectors in the MWIR to detect burnt cereal chips. The emissivity values of the skin of vegetables and fruits change when bruised or rotten, suggesting that IR detectors could eventually be applied to their inspection. Rotten corn kernels also could be detected, as well as rotten grains of wheat, barley, rice, etc. Rather than detect changes in heat, as is done in most other applications, IR detectors would be used to detect changes in emissivity in food processing applications, which come about from rotten foot, burnt food, discolored food, etc.

It is worth noting that infrared *thermometers* are prevalent as tools for process control, but that unless sophisticated, two-dimensional IR detectors become extremely inexpensive -- under $5,000 -- they will not be able to make inroads into this market. Infrared thermometers have carved out a niche in the temperature sensing market where direct-contact devices such as thermocouples and resistance probes would not work well. IR thermometers are preferred in many cases where the target object is moving or would be damaged or contaminated by direct-contact devices. Infrared systems are also preferred in settings where contact probes would either be destroyed or would be worn down by the temperature being measured (as is the case in molten metal production). In addition, infrared thermometers generally respond faster than direct-contact devices, responding in less than one second compared with one minute. They are used in ovens to monitor temperatures of products, such as metal auto parts during paint curing. Finally, infrared thermometers are sometimes the only technique available to measure temperature where the target object is inaccessible.

Simple infrared thermometers are widely employed in glass, steel, or plastics processing, to monitor the temperature of molten material. At such high temperatures, contact probes would deteriorate. They are used to control the temperature of lithographic plates during the plate-making process. They are used to control the temperature of extruded thermosetting plastics. They are used to control temperatures in food processing to avoid damage to or contamination of the product. The instruments also ensure proper sealing of polyethylene bags, complete curing of tires and other rubber products, adequate drying of adhesives, inks, laminates, and coatings, adhesion of epoxy coatings on steel pipes, the characteristics of polypropylene film, and proper processing of a wide variety of other products.

Although the commercial firms which sell infrared detectors have tried for years to penetrate these process control applications, end-users appear content to remain with unsophisticated, point detectors. So despite much speculation about the potential for infrared detectors to overtake point radiometers, pyrometers, etc., some applications will remain "low-tech," and probably do not require sophisticated detectors, unless prices fall dramatically.

Systems Design. Four essential system design features apply to IR detectors for the process control market.

First, cryogenics are not desirable on factory floors, where equipment requiring high-maintenance upkeep are generally avoided unless there are no alternatives. IR detectors cooled by TECs, or uncooled altogether, are more likely to find a market foothold, according to virtually all end-users we contacted.

Second, web inspection applications call for staring *linear* IR detectors, rather than two-dimensional ones, because the web moves steadily underneath the machine vision equipment. Some systems integrators have used simple Time-Delay Integrated (TDI) images, which use a small staring array (about 40 x 16), integrating images gathered from the web passing by underneath.

Third, the speed of image acquisition is paramount. With a stream of metal, paper, plastic, or fabric running over 1,200 ft/min underneath a detector, a throughput of 1.23 MHz is required.

Fourth, the more successful vendors in the visible-light CCD market have already packaged algorithms into primitive "tools," so that planning for each new application does not have to start from scratch. In addition, they have developed sets of generic tools, combinations of which can meet the requirements of various applications.

MCT-based detectors and InSb-based detectors have the best potential of any material to succeed at these demanding applications. Staring detectors of either could achieve speeds of >1.23 MHz. MCT, however, offers the 8-12 bandwidth which may be able to see better through misty metal web applications, and offer more contrast points to integrators of automated inspection systems.

Market Analysis. As more companies move toward semi-and fully automated manufacturing processes, machine vision is becoming an increasingly critical ingredient for success in industrial enterprises around the world. Infrared cameras are among the newest tools used by machine vision system designers, and potential applications abound. Many of these applications remain in early research stages, since IR technology was introduced to process control only three or four years ago.

Nonetheless, infrared machine vision is becoming a key element in many industries' manufacturing strategies because of its potential to improve product quality and consistency, reduce costs, and speed production. Although many industries have relied almost exclusively on human vision, machine vision has replaced it in process control tasks which are rapid and repetitive. Can ends, for example, can be inspected for cosmetic flaws at the rate of 2,000 cans/minute and dense printed circuit traces can be inspected for shorts, nicks, and other defects very rapidly, as well. Virtually every one of the end-use industries which could employ machine vision has investigated infrared detectors to some extent, including: agriculture, containers, aerospace electronics, fabricated metal parts, food, glass, paper production, plastic, primary metal, rubber, semiconductor, textile and apparel, and transportation manufacturers. The only three industries which did not yet employ IR detectors, according to our surveys, were pharmaceutical, printing, and wood products.

In almost all instances of process control where IR imagers could provide tremendous benefits to manufacturers in automated quality control, much simpler, single-point IR detectors have met with earlier success. The industries most likely to move from single point radiometers to linear or staring infrared imagers, despite steeper costs, are either ones which require 100 percent inspection of output (such as metal and paper production along webs), or ones in which each end-product is very expensive (automotive and machine components, rigid injection molded parts, or wafers, for example), or ones with extremely high rates of automated throughput (all web production lines, integrated circuit assemblies, food inspection).

The paper manufacturing industry in particular illustrates another manner in which IR detectors may become integrated full-time on assembly lines to monitor product quality. Before line scanners became available to paper mills, infrared cameras were used frequently to troubleshoot on equipment which was producing "streaks," which are areas of high moisture on paper. Most of the industry-wide work was performed by consultants who arrived with sophisticated thermal imaging cameras like those from Agema, Inframetrics, or FLIR. IR inspectors would begin at the reel, capturing the profile of the streak on the paper web, and follow several hundred feet along the web machinery until the spot of high moisture content disappeared. Once the origin of the streak was found, infrared imagers would continue to view the paper web, while adjustments were made to machinery until the streak disappeared.

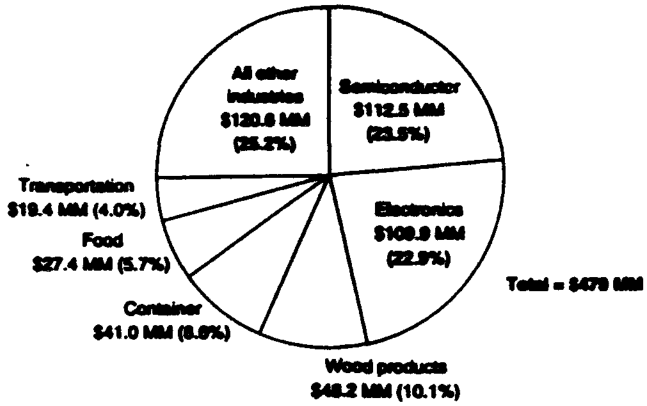
Within the last three years, paper mills have begun to demand linear scanners which can offer 100 percent inspection of an entire web, 24 hours a day. This allows manufacturers, of course, to detect the earliest deviation in quality, and take corrective action before webs have to be discarded.

This evolution of the use of infrared detectors, from part-time troubleshooters to full-time line inspectors, is typical of the radiation of infrared equipment in the entire process control industry. As prices fall on systems, and end-users become more confident in the technology, systems will become pervasive as manufacturers move from infrequent trouble-shooting to full-time product monitoring.

According to a 1991 study by the Automated Imaging Association, the world machine vision market reached $912.5 million in 1990. North America accounted for the largest share (52.5 percent), followed by Europe (20 percent), the Far East (20 percent), and the rest of the world (eight percent). The total North American market reached $509 million in 1990, of which $479 million was attributable to major industries (see figure 1 below). That study predicts that the North American market will grow by about 13.6 percent annually, to reach $906 million in 1995. Within the market, the industries most likely to expand the use of machine vision should be pharmaceutical, container, food, and printing.

If IR detectors acquire a beneficial share of the machine vision market, as we believe, their market share could be substantial. Based on our interviews, we believe that IR detectors will gain a growing share of this market, perhaps as high as 40 percent, by the end of the decade. Several process control engineers and integrators told us that the fastest growing sectors within machine vision were those best suited to IR detectors, such as web inspection of paper, metals, sheet plastic and textiles, as well as the inspection of rigid injection-molded plastic, inspection of chemical processes, and inspection of foods. There are over 50,000 web production lines in the United States alone.

Figure 1. North American Machine Vision Merchant Market by End-User Industry 1990




Source: Machine Vision: A Market Study 1990-1995, Automated Imaging Association.

Based on our surveys, most IR process control applications should mature within three to five years. A summary is given in table five below of the applications, time to market, and a projection of the number of units which could be sold annually.

**Table 5. Times to Market and Potential Market Sizes for IR detectors in Process Control**

| Application | Time to Market (Years) | Number of Potential Units Sold Annually |
|---|---|---|
| Weld Control | 2-3 | 300 |
| Web Inspection: | | |
| Metal and Plastics | 0-3 | 2,000 |
| Printing Paper | 0-3 | 1,000 |
| Food Processing | 2-3 | 500 |
| Textiles | 0-3 | 1,000 |
| Glass Manufacturing | 0-3 | 500 |
| Chemical Processes | 3-5 | 500-1,000 |
| Injection Molded Plastics and Metals | 3-5 | 1,000 |
| Semiconductor Wafer Cooling | 2-3 | 500 |

End-users whom we interviewed were willing to pay as much as $250,000 for an IR inspection system which would monitor several production points at once. More realistically, the mean price for most units is likely to be between $25,000 and $50,000. On the high end, several firms, especially those with metal web inspection equipment, would pay about $75,000 to $100,000 to be among the first to integrate IR detectors into their production lines. Chemical and pharmaceutical companies would also prize IR detectors which can monitor the rate and efficiency of chemical reactions, paying up to $75,000 per system. On the low end, systems for less demanding applications, such as glass manufacturing and automated food inspection, would cost closer to $25,000. Altogether, the market within about five years could approach about $560 million.

MCT-based detectors are well situated to capture a large share of this market for many reasons. They are among the fastest infrared materials available, and are therefore the best option for high speed processes, required for almost all these applications, but especially for web inspections. IR detectors based on less sensitive IR materials, such as PtSi, PbSe, and PbS, are not suitable for high speed applications. MCT, moreover, can easily image from several feet away, as is required in most web inspection applications, through mist, dirt, and other obscurants. MCT-based detectors also offer the resolution necessary for many defect-detection applications in web inspection, glass manufacturing, semiconductor wafer cooling, and damaged food inspection. MCT-based detectors are also the only devices that offer radiometric (absolute temperature determination) properties; these are required to monitor chemical processes, weld control, and semiconductor wafer cooling. MCT-based detectors are also the only IR systems to operate in the LWIR, which is preferred by designers of metal web inspection systems, because it sees through lubricant/coolant mist better than LWIR wavelengths. MCT-based detectors operating in the mid-infrared wavelengths, on the other hand, are particularly well suited for factory floor operations because they can be placed on a TEC, and are virtually maintenance free.

Two IR materials which may compete with MCT for process control applications are InSb and PtSi-based CCDs. Detectors based on InSb have a quantum efficiency and speed of image acquisition which rivals MCT-based detectors. Although the image resolution and quality of InSb-based detectors is often inferior to those produced by MCT, they may be satisfactory for many applications. Many researchers said that the technical requirements for applications such as web inspection, glass manufacturing, and inspection of injection-molded parts were demanding enough to rule out the use of PbS, and PbSe- based detectors, but could be fulfilled with either MCT- or InSb-based detectors. The ultimate leveler, as in other applications, could then be the cost associated with MCT- or InSb-based systems, with InSb running currently several thousand dollars cheaper per machine vision system.

Another competitor, at least in the short term, could be infrared CCDs, made of PtSi. The market for visible-light machine vision has been completely dominated by CCDs, so systems integrators and researchers are naturally more familiar with CCDs and expressed an interest in infrared CCDs. Over 130 firms produce visible-light CCDs for the process control market, whereas only about 30 firms exist which either manufacture or integrate IR CCDs into process control systems. Although MCT-based detectors offer superior performance, speed, and quantum efficiency, infrared CCDs offer higher resolution (up to about 1,024 X 1,024), usually better reliability, and a technology familiar to integrators.

Altogether, the process control market is still in its infancy. Any number of promising applications have been suggested, but remain unrealized. Within about five years, research on most of these applications will bear fruit, offering a very significant market for sophisticated IR detectors.

Suppliers

All the major commercial infrared firms sell their cameras in the process control markets, including FLIR systems, Amber, Agema, and Inframetrics. There are, however, two relative newcomers who sell stripped-down IR cameras which have little accompanying analytical software or user-friendly controls and extras, and which may be well suited to applications in process control.

Santa Barbara Focalplane in Goleta, CA, is a Westinghouse partnership manufacturing its own InSb focal plane arrays, and integrating them into its line of ImagIR cameras. The cameras are based on a 128x128 InSb detector array which operates in the MWIR and is cooled to 60 to 80°K, and costs $35,000 alone. Array quality is extremely good, with operability greater than 99 percent, and array non-uniformity under 3.5 percent. The ImagIR cameras are also radiometric. An ImagIR camera with an open, pour-fill dewar costs about $55,000, although such a system would be better suited to non-destructive evaluation than low-maintenance, assembly-line, process control applications. The same system, with a 320x240 pixel InSb focal plane array, costs $90,000; the 320x256 costs $60,000 alone. With a Stirling close-cycle cryocooler, the smaller, 128x128 detector system costs $95,000. The manufacturers do not offer a Stirling closed-cycle 320x240 system for sale.

Cincinnati Electronics, in Mason, Ohio, has sold line array and two-dimensional arrays in MCT, InSb, and indium arsenide (InAs) for many years, and has recently introduced its IRC-160 line of InSb focal plane array-based infrared cameras. The 160x120 MWIR InSb focal plane array has a pixel operability over 99 percent, and is said to have an NETD of 0.025K, although users said 0.1°K was more realistic. Using a Stirling microcooler, the IR camera is portable, looks like a video camera, and images at video scan rates. The camera retails for $65,000.

By comparison with the commercial market InSb-based camera suppliers, there are several PtSi CCD suppliers interested in supplying the process control market. Mitsubishi, represented in the United States in Cypress, CA, sells the IR-M500 IR camera, based on a 512x512 PtSi

Schottky-barrier focal plane array. It improves on the company's existing IR-5120C thermal imager, but is half its weight and one-third its size. The IR-M500 includes a cryogenic Stirling cycle cooler. Although the manufacturer claims an NETD of 0.15°C, outsiders said 0.2°C was more realistic. The cameras scans at 60Hz. The IR-M500 has been reduced in price to $40,000, which is a very low price by comparison with InSb-based systems.

Other firms which produce CCD cameras and are involved in the PtSi-based camera market are Eastman Kodak, in Rochester, NY, David Sarnoff Research Center in Princeton, NJ, Hamamatsu Photonic Systems, Inc in Wakefield, MA, and DALSA, Inc. in Ontario, Canada. None of these firms, however, appears to have yet made serious inroads into the process control markets, and the all rely predominantly on the sales of visible light CCDs for which the market is mature.

## Remote Sensing

Some of the most diverse and innovative applications for infrared thermography have been proposed in the area of remote sensing. In these varied remote sensing applications, as in the non-destructive evaluation market, expensive and highly sensitive infrared cameras with extensive analytical hardware could fill a great number of small market niches. All together, we estimate the remote sensing market for IR detectors will be worth $620 million within about five years.

Infrared detectors, many based on HgCdTe, were placed on the earliest satellites for applications in agriculture, cartography, erosion mapping, geology, hydrology, meteorology, and oceanography. Infrared detectors are now finding extensive uses as airborne sensors, as well. In this emerging market, focal plane array IR systems could be used in a slew of applications, such as mapping forest fires, assessing oil spills, detecting gas leaks, locating and mapping leakage at hazardous waste sites, mapping civil and industrial outflow into waterways and locating hidden underground objects such as piping and ducts in buildings, underground mines, archeological structures, and modern underground structures. Since most applications of IR detectors in remote sensing relate to environmental assessments, this market for IR detectors is likely to grow in concert with the market for environmental engineering, and the need to assess toxic waste sites, water quality, and soil contamination from chemicals.

A precise definition of "remote sensing" is illusory. Ostensibly, "remote sensing" refers to the detection of objects from a distance without a need to set foot in the area being imaged, either because on-site inspections could be dangerous or expensive, or because large areas could be more efficiently imaged from above. In practice, the distinction is slight in many cases between remote sensing (RS), non-destructive evaluation (NDE), and predictive maintenance (PM). The distinction is generally one of *distance* between the detector and the object being imaged. Remote sensing views objects from greater distances than in NDE or PM, usually over twenty or thirty feet. The effort in remote sensing is to survey large tracts of land, or subterranean objects, rather than focus on individual components, as is done in NDE and PM. As was customary among those interviewed (listed in appendix L), we consider remote sensing to include any application in which IR detectors are mounted to elevated platforms, such as cars, helicopters, airplanes, satellites, or even cherry-pickers in several cases.

In this section, we first delineate all the remote sensing applications which could prospectively use infrared detectors, and discuss the unique systems associated with each application. We then analyze the market for these applications, including the potential size of the market, and the likelihood that MCT-based sophisticated focal plane arrays could be used in each application.

Applications. The remote sensing infrared market seems to be driven by researchers with nearly unique detectors, each of whom is seeking to open up as many applications as possible for their preferred IR systems.

Infrared remote sensing has been conducted by satellites for the largest period of time. Since commercial satellites are used only sparingly, this niche market for scientific research is limited. It deserves discussion, however, because it has fostered the development of basic remote sensing technologies, particularly those utilizing IR systems. Multi-spectral scanners (MSS) are the predominant class of devices used on these satellites. MSS devices digitally record the detected radiation in a number of defined wavelength channels or bands. They sense multiple wavelength regions of the visible, near infrared (1-3 micron), middle infrared (3-5) and thermal infrared parts of the spectrum. In the parlance of remote sensing, "middle infrared" denotes MWIR wavelengths, as "thermal infrared" does LWIR. Since wavelengths in these spectral regions are strongly affected by atmospheric scattering, the usefulness of these devices for earth surface studies differs according to the application. The principle of the multi-spectral mode of operation is the same as that of using filters on a camera to photograph limited parts of the visible spectrum; filters allow only a specific wavelength to reach the detector. For example, the Landsat 1 to 5 satellites have carried a MSS which senses four bands of the spectrum, listed in table six.

**Table 6. Spectral Bands in the Landsat 1 to 5 Satellites**

| | |
|---|---|
| Green | 0.5-0.6 micron (band 4) |
| Red | 0.6-0.7 micron (band 5) |
| Near Infrared | 0.7-0.8 micron (band 6) |
| Near Infrared | 0.7-1.1 micron (band 7) |

An additional scanning device called the Thematic Mapper operates on Landsats 4 and 5. This instrument has the seven spectral channels listed below in table seven.

**Table 7. Spectra Bands of Thematic Mapper on Landsats 4 and 5**

| | |
|---|---|
| Blue/Green | 0.45-0.52 micron |
| Green | 0.52-0.60 micron |
| Red | 0.63-0.69 micron |
| Near Infrared | 0.76-0.90 micron |
| Near Middle Infrared | 1.55-1.75 micron |
| Middle Infrared | 2.08-2.35 microns |
| Thermal Infrared | 10.40-12.50 microns |

Staring arrays and CCDs are becoming more popular in satellite sensor systems. In satellite lingo, they are called "pushbroom" scanners because images are formed by the sensor being swept forward by the platform's velocity. The SPOT HRV uses a pushbroom scanner with four arrays of 1728 detectors. The Multi-spectral, Electronic, Self-Scanning Radiometer (MESSR) currently carried on the Japanese MOS-1 satellite is also a pushbroom scanner. A number of future sensors are being developed using this technology. The Modular Optoelectronic Multi-spectral Scanner (MOMS) which was carried on the Space Shuttle used linear array sensors. Simpler, SPRITE or single point-based IR detectors are part of the TM sensor on Landsats 1,2,3,4, and 5 operating at 1.55-1.75, 2.08-2.35 and 10.4-12.6 microns, on the VISSR sensor of GMS (10.5-12.5 microns), the AVHRR sensor of NOAA (3.55-3.93 and 10.5-11.3 microns), and the CZCS sensor of NIMBUS (10.5-12.5).

Unfortunately, mid-wave and long-wave infrared *can not* be used in remote sensing's leading day-to-day application, which is crop assessment. The assortment of satellite and airplane-deployed imaging systems which look for crop damage, pest infestation, blight, plant moisture content, weeds and illicit crops work predominantly at wavelengths no longer than 2.5 microns. Since green vegetation typically falls off in reflectance and absorption characteristics after short-wave infrared (SWIR), most multi-spectral scanning systems focus on the near-infrared, SWIR, green, and red light. The traditional visible and near-infrared channels which are most commonly used by scientists for crop assessments from satellites range from 0.42 to 1.05 microns.

But the scientific community has an array of uses for IR detectors outside of crop assessment. Space-borne IR detectors are integral to the applications listed below:

- Cartography
  - Geodesy and photogrammetry
  - Merging other data with remote sensing for map presentation
  - Use of stereo imagery for topographic mapping
  - Compile and update thematic maps of various resources
- Engineering
  - Routing power lines
  - Designing transportation networks
  - Site selection
- Erosion mapping
  - Mapping and monitoring eroded areas
  - Predicting potential erosion sites
  - Monitoring land degradation and desertification
- Geology
  - Identifying lineaments and other structural features
  - Mapping geomorphology and geobotany
  - Analyzing landform and drainage
  - Identifying rock types
  - Identifying oil seepage
  - Access planning and base map preparation
- Hydrology

Detecting near-surface aquifers for ground water storage
Monitoring irrigation performance and usage
Supplement investigations for flood plain management
Monitoring on-farm water storage
Mapping current and potential salinity sites
Estimating soil moisture and surface temperature
Planning engineering constructions and monitoring their effectiveness

Meteorology
- Route atmospheric studies of temperature and weather patterns
- Mapping cloud cover, patterns, composition, and temperature
- Weather forecasting
- Flood prediction and monitoring
- Storm warning and damage assessment
- Locating and tracking cyclones
- Monitoring bushfires
- Mapping snow-cover, run-off and melt rate
- Detecting chemical and/or particulate composition of the atmosphere
- Climate studies
- Vertical temperature and humidity profiling
- Deducing geopotential height and upper level wind velocity
- Mapping cloud drift winds

Oceanography
- Estimating sea surface temperature
- Ocean color mapping
- Mapping of sea surface and sea floor topography
- Detecting navigational hazards
- Mapping ocean currents, wind, and wave action
- Detecting oil spills, thermal effluent or other pollution
- Mapping fish populations and movements
- Identifying upwelling areas of biological significance
- Studies of sea ice and glacial movement

Renewable Resources
- Land cover inventory and monitoring
- Modeling vegetation structure
- Detecting land-use changes
- Mapping landform types
- Mapping potential brushfire status
- Assessing the impact of natural disasters such as fire or drought.

Infrared detectors on aircraft also offer an abundant number of applications. We describe 16 remote sensing applications below in which IR detectors could make, or have made, contributions. These applications are not at all as pervasive as, say, biomedical or predictive maintenance ones, and the market for RS applications remains modest. Although these applications are straightforward and the utility of thermography undisputed, the remote sensing market remains "esoteric" by outside estimates. Indeed, most remote sensing application are being developed by federal laboratory, led by lawrence Livermore National Labs; and only a few private companies are addressing these niche markets. Each sensor produced for RS applications, however, needs to be very sophisticated and will therefore be expensive, and could readily benefit from focal plane array technology.

System designs for the use of IR detectors for remote sensing have gone in three directions: dual- band, IR combined with Ground Penetrating Radar (GPR), and Laser Backscatter. Each of these systems performs successfully, according to users we contacted. The BAGI laser-backscatter system is a specialty item which would filter incoming IR signals to specific wavelengths, but the other two systems -- dual-band and IR-GPR -- are competing for similar applications. Both of the latter two systems have similar capabilities, and research on both sides are pushing forward research into remote sensing applications for IR. Together, the applications which have been developed for remote sensing are substantial and varied.

Dual-Band Infrared Detector. The most popular infrared detector system for remote sensing operates simultaneously in the MWIR and LWIR, using MCT-based arrays. It is called a dual-band detector, and was developed in the early 1980s by a team at Lawrence Livermore National Laboratories (LLNL). Daedalus Enterprises, Inc. in Ann Arbor, MI, has been selling the only commercial "Airborne Bispectral Scanner" system with the same capabilities as LLNL's dual-band system. In particular, researchers have been pursuing applications specifically in firefighting, oilspill assessment, and the detection of underground objects ranging from live mines to archeological remains.

LLNL researchers developed an arms control verification technique using IR detectors as early as 1979. They studied surface-temperature signatures near ground zero before and after a nuclear explosion to see how, and for how long, soil "fluffing and slapdown" after an underground nuclear test changes the soil's thermal diffusivity, and consequently, its heating and cooling properties.

More recently, LLNL's dual-band IR system has been tested and used preliminarily to locate hot-spots and map both large urban, and forest, fires. When fires break out, spread, and endanger large population areas or large pockets of natural resources, aerial images could give fire fighters the first high-resolution overview of the firelines, hot spots and smoldering areas about to reignite. In urban fires, firefighters need to know quickly the direction and speed of spread of a fire, to avoid disastrous loss of lives of property. With forest fires, firefighters need to knowp the perimeter of the fire, and locate its direction and speed of spread. In both urban and forest fires, firefighters need to look through smoke, haze flames and debris to locate hotspots. Infrared pictures, which see through such obscurants, can help firefighters to assess the fire, decide where to concentrate forces, where to evacuate, and where precisely to air drop water.

Until recently, on-board detection systems for fires were film-based and required the planes to land to process the film. This caused long delays before the data could be evaluated. A newer technique has been to encapsulate films or videotapes in Luxan cartridges, which are pneumatic tubes, and toss them to ground crews. Finally, research led by the Jet Propulsion Lab has begun to acquire digital IR terrain data, using scanning IR detectors, relate it to maps of the ground, and then send the data instantaneously by VHF to ground crews.

One system designed by NASA's Ames Research Center in Mountain View, California, using technology from LLNL, was used to fight the October 1991 Oakland fire. It used an Ames C-130 turboprop equipped with two thermal scanners designed for high-temperature reconnaissance. Flying at altitudes between 5,000 and 18,000 feet, infrared maps were obtained with MCT-based linear arrays in both MWIR and LWIR. The MWIR array was used to pick out hot-spots (where temperature exceeds 600°C), flames, and embers, while the LWIR array thermally mapped the general area affected by the fire. IR images were coupled with data from the Global Positioning System to produce precise maps with empirical referents.

Underground objects also can be located, identified, and mapped, with dual-band infrared detectors. For example, underground aquifers up to about 60 meters beneath the surface could be located and mapped. Thermography is cheaper, faster, and as adequate as deep-pole measurements, which are the conventional method. Whereas deep-pole measurement is a hit-or-miss technique which only spot-checks underground water tables, dual band IR systems can assess an entire region from the air, quickly and efficiently.

Researchers also have developed a dual-band IR system to locate underground mines by aerial overflights, called Temperature Evaluated Mine Position Survey (TEMPS). The Army has been searching for over forty years for an effective mine detection system. Dual-band thermography has performed extremely well in detecting shallow mines. Military technology has had trouble locating small mines that were either buried, scattered in a field of clutter, masked by foliage, or shaded by trees, but the TEMPS system is able to locate, discriminate and subtract out surface-emissivity variations, thus minimizing background confusion.

The TEMPS system has worked flawlessly in several test scenarios. For example, in the early part of 1991, a demonstration was conducted in a desert environment at the Yuma Army Proving Grounds in Arizona. During a midnight overflight of the target zone, all 36 live M15 and M19 mines were located. These live mines had been buried in a patterned array, 0.5 to 6 in deep in a sand cover similar to the Kuwaiti terrain. Potential false alarms were planted at the site, including tank tracks, a dry creek bed and disturbed sand. These were removed from the data through signal processing. By contrast, daytime flyovers located 88 percent of the live mines buried up to 6 inches deep.

Archeological remains also can be located using the dual-band IR system. Thermography could serve as an economical means to help archeologists find irrefutable proof of underground remains without needing first to invest in digging and sorting. Other uses of underground remote IR sensing, which are developed fully under the section on surveillance, include drug-traffic surveillance and interdiction, such as locating underground structures like tunnels or drug depots.

Another kind of dual-band sensor, using both UV and either LWIR or MWIR is becoming popular for the assessment and mapping of oil spills. Radar has been used to map oil spills, but radar systems have a high clutter rate and read too many false positives to be considered reliable. Airborne bispectral scanners, operating in both the LWIR and UV, are providing better results. Oil has a different emissivity than water and can be clearly delineated using an IR detector. A few days after spillage, oil sinks just beneath the water's surface, where it is hard to detect by radar. In fact, clean-up of the Alaskan seacoast following the spill from the Exxon Valdez was monitored using bispectral UV and IR detector systems manufactured by Daedalus, Inc. The UV assisted in determining the total area of the oil slick, while IR determined the thickness of the oil.

Infrared and Ground Penetrating Radar. A second type of system used increasingly to detect underground objects couples IR thermography and Ground Penetrating Radar (GPR). IR thermography can detect substances underground because as the sun's energy penetrates soil, all similar surface and subsurface material absorb and store this energy in the same manner. If subsurface differences are present in the soil, the rate at which the energy is received, stored, and released will create an abnormal temperature profile on the surface of the site. Chemicals leeched into soil, for example, change the soil's thermal properties, as do solid objects such as voids, deteriorated backfill, tanks, and/or contaminated soil plumes. Thermography is an excellent tool for locating subsurface anomalies by efficiently measuring variances in surface temperature. However, thermography can only reveal surface thermal characteristics created by subsurface items, and cannot currently determine depth, construction type, or other characteristics of subsurface objects. To determine those characteristics, ground penetrating radar is used.

Ground penetrating radar uses a transducer to produce controlled electromagnetic pulses that are transmitted into the subsurface area highlighted during thermographic inspection. The controlled pulses penetrate the investigation area and are echoed to a receiver. The electromagnetic pulses show the underground conditions of a given site. Although GPR is an excellent tools for pinpointing and characterizing subsurface waste sites, it is only a "point source" measurement system. It needs to be used in conjunction with thermography to assess large areas. Therefore, sites suspected of containing hazardous or contaminated waste or toxic chemicals can be inspected first by infrared thermography as a primary testing technique and then ground penetrating radar as a secondary technique. Aerial overflights with thermography would be used to survey broad ground areas and locate spots with anomalous temperature profiles; GPR would then be used on the ground by technicians to spot-check depth and composition of those specific spots with abnormal temperatures. This technique combines infrared's strength to survey large areas quickly with GPR's ability to detect specific depths and composition of underground objects.

The leading applications for a combination IR/GPR system are the detection of toxic wastes underground, and assessments of surrounding areas for leakage and underground seepage into the water table or soil nearby. Millions of tons of environmentally dangerous wastes are suspected of having been disposed of in the US. According to the infrared community, infrared thermography in conjunction with ground penetrating radar is extremely effective in detecting buried toxic waste sites, buried tanks/pits, and tank/pit leak plumes.

The detection of these toxic substances is essential to three separate communities. First and foremost, insurers and land owners are extremely concerned about insuring or selling contaminated land which is a liability. The law is requiring increasingly that before new construction may be initiated on lands possibly containing toxic substances, the waste must be located and cleaned up. Depending on the nature of the purchase, the location or confirmation of buried waste could be a decisive factor in decisions to purchase or insure property. Secondly, environmental engineers want a comprehensive and inexpensive system to assess known toxic waste sites to ensure that all barrels are safe and sealed, and to monitor plants which either produce or work with toxic chemical substances and may be releasing those chemicals into the environment. Third, communities and the federal government are aware increasingly of sites of abandoned and undocumented toxic waste, and need a system to identify the extent of what is buried underground. If unremediated, of course, toxic waste could pollute local water, aquifers, soils, and crops. These three communities could well make use of the joint IR/GPR technique for underground assessment of sites.

The two traditional methods for finding contaminated waste are not as effective as thermography. One method of uncovering subsurface waste is placing monitoring wells at the site, or coring numerous areas. The cored materials would then be analyzed or observers would watch for telltale signs of escaping gases. The problem with this method is it does not work well with large sites, and contaminated materials could be missed by inadequate coring and monitoring of wells. Coring and setting up monitoring wellsis also more expensive than IR thermography. Finally, there is the added risk of coring into an existing filled tank which could increase the cost of clean-up. Another testing method, magnetometer (also called EM testing), has also met with only limited success since test sites contain many metallic objects on and beneath the surface which yield false positives. In addition, this technique cannot locate contaminates that have leaked into surrounding soils.

We were told of two case studies of waste site detection with IR and GPR techniques. At an air force base in California, engineers used thermography and ground penetrating radars to help search eighty-nine sites where underground storage tanks were suspected. Data from electromagnetic investigation produced limited results due to the large amount of metallic objects within the base's soil. From a lift truck elevated to fifty feet, however, thermographers were able to survey an area of 10,000 square feet in each of those 89 locations, and finished their inspection in only fifteen hours. Thirty-eight sites were tagged as potentially containing buried storage tanks, and examined with ground penetrating radar. Thermography limited the field of view for inspection by GPR to about 400 square feet at each site. Results were obtained in twelve hours. In the end, combined IR and GPR investigations revealed the location, size, depth, and construction type of 36 underground storage tanks.

In the second instance, IR and GPR techniques were used to survey a 1.6 acre site in the New Mexico Desert where researchers from Los Alamos National Labs were suspected of having dumped contaminated radioactive and mixed waste since the 1950s, possibly containing radioactive tracers, contaminated oil, fuel drums, and concrete since the 1950s. Using aerial overflights for thermography and GPR, investigators documented several trenches and pits containing underground storage tanks, and even a fifty-gallon tank outside the fenced-off perimeter of the contaminated site. Soil areas were also identified which could require extensive rehabilitation.[45]

This IR/GPR detection technique is not limited exclusively to toxic waste drums. Buried tanks of all kinds can be located and assessed for leakage. For example, thermography can be useful in environmental site assessments at industrial plants, to help locate buried industrial waste materials, underground storage tanks, and miscellaneous waste items as small as 55 gallon drums. In another case study, a thermographer took part in a Phase II environmental site assessment of a 50-acre industrial plant site, successfully finding five areas containing subsurface piping and metallic debris.[46] In another case, a thermographer, surveying land which was to be dug-up for construction, located underground storage tanks which had been left over twenty years before by a former gasoline station.[47]

In other cases, suspected grave sites have been found using infrared detectors with GPR. For grave site detection, "dead air spaces" beneath the soil slow down the flow of energy as compared to solid, compacted soil. IR images taken during daylight hours show a pattern of warmer areas denoting grave sites; after dark, a pattern of cooler areas designates grave sites. In one case study, city engineers suspected buried grave sites within a park area and inspection by

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[45] Gary Weil, "Nondestructive Remote Sensing of Hazardous Waste Sites," Thermosense XV (April 1993).

[46] G. Weil, "Non-Destructive, Remote Sensing of Buried Tanks," Unpublished

[47] Weil Waste Site

IR and GPR revealed a plague cemetery from the Civil War era. In another case, thermography mapped undocumented, old burial sites in the proposed path of St. Louis' mass transit system.[48]

Another use for a joint IR/GPR system, limited in market potential, could be detection of archeological remains buried underground. For example, archaeologists believed that a paved parking lot near the Mission Plaza in California covered the remains of the Santa Cruz Mission cemetery. Operating 24 feet above the ground from the platform of a forklift truck, the IR dual scanners were able to capture thermal images showing a total of fourteen 40- to 60- foot long parallel trenches, a cemetery wall, and the western extension of a barracks identified earlier adjacent to the parking lot. The foundation was found to be about 0.5 meters thick.

Another application for IR-GPR systems is pipeline leak detection. Thermography has been used to test pipelines in chemical plants, water supply systems, steam lines, natural gas pipelines, and sewer systems. Thermography could test in-place, buried pipelines for subsurface pipeline leaks, voids caused by erosion, deteriorated pipeline insulation, and poor backfill. Its non-contact, non-destructive ability to inspect large areas from above ground with 100 percent coverage and to locate subsurface leaks as well as the additional capability to locate voids and erosion surrounding pipelines make IR-GPR systems' capabilities testing capabilities unique.

According to thermographers, most pipelines, whether they contain oil, chemicals, water, steam, gas, or sewage, are designed to last 20 to 25 years. With buried pipelines, maintenance crews are usually called in after leaks have been detected above the ground, and by then valuable time and resources have been lost. Pipeline leaks also cost much more than if parts were replaced as part of a maintenance program in which IR thermography was a link. With underground sewers, where more predictive maintenance has been attempted, the two techniques that have been used traditionally to locate impending failures are based on finding voids around the outside underground sewers, which are expensive or not as reliable as IR thermography. First, engineers could conduct a crew to visually inspect the sewer surface areas by physically or electronically entering the underground sewers. This is very costly by comparison with IR thermography. Second, engineers could take soundings, borings, and core samples at random or on a matrix pattern. Both techniques have disadvantages because they are expensive and labor-intensive, and can be dangerous, often exposing workers to dangerous chemicals or gases and sometimes extremely high temperatures. Also, the techniques are limited because they only spot check, and are not as comprehensive as thermography. Thermography can show leaks quite

[48] G. Weil and R. Graf, "Infrared Thermographic Detection of Buried Grave Sites," Thermosense XIV (April 1992) pp.347-353.

dramatically, along with leak plumes and areas of pooling.[49]

Another area of application for the joint IR/GPR technique is remote non-destructive testing of bridge, highway, and airport pavements. As the national transportation infrastructure ages, new technologies need to be found for evaluating these concrete structures so that their maximum value and life can be realized. But concrete, by its very nature and construction method, is highly variable and does not lend itself to testing by nondestructive methods as easily as steel products, for instance. Several leading societies, including the American Society for Testing and Materials (ASTM), the International Standards Organization (ISO), and the British Standards Institute (BSI), have set several criteria for testing concrete infrastructure:

1. They must be accurate, with the ability to determine shape, size, and depth of defective areas
2. They must be non-contact and nondestructive
3. They must be able to inspect large areas as well as localized areas
4. They must be efficient in terms of both labor and equipment
5. They must be economical
6. They must not be obtrusive to the surrounding environment
7. They must not inconvenience the structures' users

According to thermographers we contacted, infrared thermography and ground penetrating radar can foot the bill. Although testing of concrete has been accomplished traditionally by physical spot corings, that technique is expensive, time consuming, and destructive. Thermography overcomes those barriers. As the cold night sky acts as a heat sink to draw the heat energy out of the ground or pavement, the movement of energy through different areas of thermal conductivity such as voids, delaminations, or sandy concrete cause the pavement's surface to have a different temperature patterns. During daytime testing, voids may manifest themselves by warmer surface temperature patterns, while at night the same spots would be colder.

From a car, pavements as wide as 36 feet have been inspected by IR thermography at up to 10 miles per hours. Exact void sizes and locations for such voids are determined and plotted on a drawing to scale. During a second pass, specific anomalies are characterized using ground penetrating radar to approximate depth, thickness, and whether they are to be considered to have been caused by overlay debonding, half depth problems, or full depth problems.

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[49] R. Graf and G.Weil, "Infrared Thermography Based Pipeline Leak Detection Systems" Thermosense XIV (April 1991, vol. 1467) pp. 18-33.

In one case study, a company we contacted performed over 100 bridge deck inspections for the Illinois Department of Transportation. These decks ranged from some of the world's largest, such as the Poplar Street Bridge complex over the Mississippi River, to some of the country's smallest, such as those in rural areas of upstate Illinois. The company also inspected a 4,000 foot-long two lane section of Interstate highway I-70 in Kansas City, Missouri which had recently been replaced. The Missouri Department of Transportation felt that the concrete mixture used may not have been completely homogenous and that pockets of pure sand, with no binder or gravel, may have found their way into the pavement. Infrared thermography was used without GPR because of the large area, which required imaging over 100,000 sq. ft. Five areas of anomalous composition were found by thermography, four of which when inspected visually by coring were found to have loose sand or voids.[50]

Laser Backscatter System. Another system designed at the Lawrence Livermore National Laboratory in 1985 uses laser backscatter to find gas leaks. Undetected gas leaks represent a are not just a hazard to personnel at companies and the environment, they also constitute a significant loss to companies which stock gas and. The use of sniffer-type gas detectors for gas-leak detection and location in many industries is usually a difficult, painstaking, and often unsuccessful technique, eventhough that equipment prevails currently. Researchers at the Lawrence Livermore National Labs developed a systems for the Naval Sea Systems Command for remote surveillance of disabled marine vessels to detect and locate toxic or flammable vapors before personnel boarded those vessels. The system LLNL developed is called laser backscatter/absorption gas imaging (BAGI). Laser and imagers combine in a system which detects hazardous gases from leaking tanks and other sources. Afterwards, the patented technology was transferred to Laser Imaging Systems in Punta Gorda, Florida.

The BAGI technique makes small concentrations of normally invisible gas visible through the use of an infrared detector hooked up to a video screen. No sophisticated signal conditioning or data manipulation is required. A laser beam is scanned over a 14 X 18 ° rectangular field of view, and the IR detector measures the backscattered energy in the absorption band of the gas suspected to be leaking. Since most hazardous gases are strong absorbers in the IR, but not in visible light, systems use a $CO_2$ laser tunable over a 9-11 micron spectral range, and MCT-based IR detectors in the 8-12 micron window. Current systems are capable of operating at ranges up to 30m with the capability to image a tracer gas (sulfur hexachloride) leak rate of 0.016 scc/min (standard cubic centimeters per minute). Although the BAGI system does not measure the precise concentration of gas leaked, the image it creates darkens with higher concentrations of gas.

[50] G. Weil, "Nondestructive Testing of Bridge, Highway, and AIrport Pavements," Unpublished

There are numerous applications for gas leak detectors like the BAGI, many of which cross the lines between remote sensing and non-destructive evaluation. In each case, traditional inspection systems exist but are either expensive, cumbersome, or time consuming. Tracer gases such as sulfur hexachloride are used commercially in component leak testing applications before filling components with gas which is considered toxic to personnel or environmentally unsafe, as in the case of freon. Most IR systems would be optimized to work in the LWIR where that gas can be detected. One of the first commercial applications for such a systems could be in the appliance industry where air-conditioner manufacturers performs on-line leak detection of condenser coils. Before filling the condensor coils with refrigerant, they are pressurized and tested with tracer gas. Coil assemblies are conveyed past the inspection scanning station and the leaks pinpointed on displays. For now, the coils are then immersed in "dip tanks" where they are inspected for bubbles in order to pinpoint leaks. Dipping is expensive and cumbersome to perform. Instead, an IR detector could be substituted and inspect coils for tracer gas leaks, without needing to dip the condensor coils.

Numerous applications are also foreseen in the auto industry for BAGI-style systems. For example, radiators could be inspected in a set-up similar to coil assemblies. Radiators which have failed the usual production-line pressurization test could be pressurized with tracer gas to detect any leaks before installation, instead of using the traditional technique of using ammonia-sensitive paint. Gas tanks also could be filled with tracer gas, and although not designed to be totally airtight, could be tested with IR detectors for leakiness beyond an acceptable threshold.

Chemical processing plants could replace traditional and inefficient methods of gas leak detection with multi-spectral IR detector systems designed to view a variety of gases. The method currently used for facility monitoring involves a two-step procedure. With the current approach, a hard-wired network of electrical leak sensors is used to detect concentration threshold levels for specific predetermined locations at a storage facility and to feed alarms back to a central station. Portable "sniffers" are then used to manually inspect the area where the alarm occurred in order to pinpoint the leaks.

Future applications include deployment of airborne systems to overfly facilities and above-ground pipelines for real-time inspection and rapid videorecording of leaks without endangering personnel and with improved accuracy. For example, a BAGI system could remotely detect and locate leaks in natural-gas (methane) pipelines and distribution stations. Most remote-detection systems in use today rely on secondary indicators such as browning of grass or foliage at a leak site, followed up by inspection with handheld sniffers. Methane has a strong absorption band at the 3-4 micron region. A system developer remarked "this would answer a huge need to allow suppliers and distributors alike to frequently inspect their lines and equipment."[51]

Market Analysis. The remote sensing market offers an extremely large number of unique applications, each with modest market potential in terms of revenue. Although system designs seem to be heading in three separate directions, the number of applications continues to broaden. Price is the limiting factor.

Dual-band infrared systems developed at LLNL have not been commercialized, but researchers estimate that such systems would cost at least $80,000. That is also the starting price for Daedalus Enterprises' Airborne Bispectral Scanner. Both LLNL's and Daedalus' dual-band systems make use of MCT-based single point detectors. Individuals at both places explained that focal plane arrays were considered for those systems, but were dismissed because they would elevate system cost even higher.

MCT-based focal plane arrays could potentially capture a large segment of the remote sensing market, for three reasons. First, the high pixel resolution of focal plane arrays could allow users to fly higher and survey larger tracts of land at once (thereby saving money and time in data-gathering overflight operations), without sacrificing sensitivity. Conversely, the high resolution of focal plane arrays could allow thermographers to increase the detail in isolated spots on the ground. Increased detail, in particular, has plagued researchers working on detection of toxic waste, contaminated waste, underground storage tanks, and live underground mines.

Secondly, remote sensing could benefit from the high sensitivity of arrays based on MCT. Since underground voids, buried tanks, mines, or effluents modify terrestrial temperatures only slightly, a mean sensitivity of about 0.1°C is required. Since the temperature differential between a foreign object and surrounding soil dissipates in proportion to its depth, infrared detectors with a higher sensitivity could image deeper objects.

Third, MCT-based detectors are the only ones to perform in LWIR, which is required for dual-band IR systems, and preferred by designers of IR/GPR systems. In fact, designers of joint IR/GPR systems began using systems that operated in the MWIR, according to those we surveyed, but switched to LWIR because it produced a higher signal-to-noise ratio. The stronger infrared signal produced by LWIR detectors is better for imaging underground objects, and has become preferred by thermographers.

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[51] H. Kaplan, "Using Laser Backscatter to Find Gas Leaks," Photonics Spectra (June 1991) pp. 98-100.

A hurdle which confronts focal plane array detectors in other markets does *not* present itself here: absolute temperature measurement. Since all applications described in remote sensing are more concerned with qualitative rather than quantitative determinations of temperature, it appears that radiometric instruments would not be an advantage in this market.

The individual markets for specific applications in remote sensing are modest except in the case of gas leak detection systems, which could sell about 500 units a year within about three years. The discovery of new applications in the remote sensing market appears to be driven by systems designers, like LLNL's or Daedalus', who create an infrared technique, and then find out what applications it can do, rather than by researchers who design altogether new systems to fulfill specific applications.

Many of these systems could soon be available, especially for gas leak detection, pipeline leak detection, forest fire monitoring, oil spill monitoring, archeological remains sensing, and gravesite detection. Several applications require more extensive and specific software development, and could be available within three years, such as toxic contaminated waste detection, storage tank detection, pavement assessment, aquifers discovery, and ice thickness determination. We believe mine detection could be the last application to develop because it would be predominantly for military use and requires extensive knowledge of thermal signatures of specific mines. In aggregate, the remote sensing market could be worth about $620 million within three to five years. Table eight below summarizes our outlook for each application described above.

Altogether, we estimate 1,200 units could be sold annually for all remote sensing applications, at average prices of $50,000. The only limit to MCT-based detectors' market potential is in price. Specialty systems for subsurface imaging (such as buried storage tanks, toxic wastes, pipeline leak detection, and highway infrastructure) have relied on MCT-based detectors, and probably will continue to do so. The less expensive, high-volume applications to be captured by the BAGI system could integrate MCT-based detectors, but entire system cost would have to be less than $20,000.

**Table 8: Summary of Applications for IRFPAs in NDE**

| Specific Application | Eventual Popularity | Time to Market (years) |
|---|---|---|
| Gas leak detection | High (Over 500 systems sold annually) | 3 |
| Underground toxic and contaminated waste detection, including sewage into waterways and illegal dumping | Medium (200-500 systems sold annually) | 2-3 |
| Buried storage tanks detection | | 2-3 |
| Pipeline leak detection | | 1 |
| Bridge, highway, and airport pavement assessment | | 2-3 |
| Forest fire monitoring | Low (Less than 200 systems sold annually) | 1-2 |
| Oil spill monitoring | | 1-2 |
| Underground aquifers discovery | | 2-3 |
| Mine detection | | 3-5 |
| Standard satellite research | | 0 |
| Archeological remains sensing | | 1-2 |
| Arms control verification | | 0 |
| Ice thickness determination | | 2-3 |
| Gravesite detection | | 1-2 |

Suppliers. There are several firms devoted exclusively to the multi-spectral remote sensing market.

∘ **Daedalus Enterprises, Inc.** in Ann Arbor, Michigan manufactures specialty systems which are placed predominantly on satellites, but are also used in aerial overflights. Daedalus states it has over 65 airborne systems in use, in over 24 countries worldwide. In the infrared, it manufactures an Airborne Multispectral Scanner (ABS) which has two scanners. One is LWIR (8.5-12.5 microns), while the other is a choice between SWIR (3.0-5.5 microns), visible/near-infrared (0.4-1.1 micron), or ultraviolet (320-380 nm). Daedalus recommends the wavelengths for specific applications listed in table nine:

**Table 9. Wavelengths Recommended by Daedalus for Various Remote Sensing Applications**

| Partial Listing of Applications | Detector Combination | | | |
|---|---|---|---|---|
| | UV | V/NIR | SWIR | LWIR |
| Geological mapping | | | | X |
| Ground water discharge | | | | X |
| Offshore spring mapping | | | | X |
| Rooftop heat loss | | | | X |
| Steamline heat loss | | | | X |
| Thermal discharge monitoring | | | | X |
| Fire detection/ mapping | | | X | X |
| Geothermal exploration | | | X | X |
| Search and rescue | | | X | X |
| Ice mapping | | | X | |
| Soil moisture studies | | X | | X |
| Thermal inertia mapping | | X | | X |
| Crop and forestry studies | | X | | X |
| Oil spill detection/ mapping | X | | | X |

Daedalus also produces an Airborne Multispectral Scanner which records up to six spectral channels simultaneously directly onto 8mm digital tape. The AMS provides calibrated thermal information for the determination of radiometric temperature relationships for various remote sensing applications. The standard sensor configuration offers a dual-element thermal infrared detector of MCT and an 8-channel, visible/ near IR spectrometers so that a total of ten spectral bands are available. It operates in the channels listed in table ten below.

**Table 10. Wavelength Channels of Airborne Multispectral Scanner**

| | |
|---|---|
| UV Channel (optional) | 320-380 nm |
| VIS/ NIR Spectrometer | 0.42-0.45μ |
| | 0.45-0.52μ |
| | 0.52-0.60μ |
| | 0.60-0.63μ |
| | 0.63-0.69μ |
| | 0.69-0.75μ |
| | 0.76-0.90μ |
| | 0.91-1.05μ |
| IR Channels | 3.0-5.5μ |
| | 8.5-12.5μ |

Daedalus recommends the spectral bands listed in table 11 for these applications.

∘ The **Environmental Research Institute of Michigan**, in Ann Arbor, MI, is a not-for-profit organization which develops multispectral scanner systems, infrared scanners, synthetic aperture radar systems, and designs image processing programs for remote sensing applications. Their accent is on scientific research.

∘ **Loral Fairchild Systems**, a division of Loral Corporation, located in Syosset, NY, was formerly the Electro-Optical Group of Fairchild Weston Systems, Inc. They manufacture airborne electro-optical reconnaissance systems, visible and infrared foacal plane arrays, and CCD detectors used in tactical and space video systems.

∘ **MS2i,** located in S.t. Quentin en Yvelines, belongs to the French MATRA Group known for its space and defense activities. They provide multispectral remote sensing systems used for civil and military applications.

∘ **Itek Optical Systems**, locaetd in Lexington, MA, develops, manufactures, and tests custom optical systems placed in satellites used for civil and military applications.

**Table 11. Spectral Bands Recommended by Daedalus for Various Applications**

| Partial Listing of Applications: | Spectral Bands | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | UV | VIS/ NIR Spectrometer Channels | | | | | | | | 3-5μ SWIR | 8.5-12.5μ LWIR |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | |
| Geologic mapping | | | X | X | | X | | X | | X | X |
| Water chlorophyll | | X | | X | | | | | X | | X |
| Water suspended Sediment | | | | X | | | | X | | | X |
| Water temperature | | | | | | | | X | | | X |
| Forest inventory | | | X | X | X | X | | X | X | | |
| Crop vigor studies | | | X | X | | X | | X | | | X |
| Fire detection/ mapping | | | | | | | | | | X | X |
| Oil spill detection/ mapping | X | | | | | | | | | X | X |

∘ A company which specializes in remote sensing applications, although it also does other IR applications, is **Entech Engineers**, in St. Louis, Missouri. The firm consults in IR thermography, doing both standard predictive maintenance surveys of electrical and mechanical equipment, but also works on more advanced applications in remote sensing. Like most consultants who work remote sensing applications, Entech has modified commercially available equipment, such as Inframetric's Model 740. In fact, **Inframetrics**, in Billerica, Massachusetts, provides probably 50 percent of the thermal imaging systems which are adopted by the remote sensing market. Even lab researchers at the LLNL say they base much of their research on Inframetrics' systems. Other suppliers are Amber Engineering in Goleta, California, and Agema Engineering, sold through a distributor in Vernoa, N.J.

## Surveillance

Sophisticated infrared detectors have found widespread usage as instruments of surveillance. Thermal imagers provide law enforcement and drug interdiction personnel the ability to observe remotely what was previously cloaked by darkness, bad weather, or deliberate attempts at concealment. FLIRs are used so pervasively for surveillance that the Airborne Law Enforcement Agency, of Tulsa, Oklahoma, reported in 1992 that 42 percent of its member agencies, which range from the Drug Enforcement Agency (DEA) to local police precincts, made use of IR technology. Police and counternarcotics agents have been familiar with military-style Flirs since the 1980s, value their unique capabilities, and have integrated them into many types of law enforcement operations. Barring major breakthroughs in new applications, the market for advanced IR detectors in surveillance should grow steadily at about five percent annually through the end of the decade, reaching $80 million by about 1996.

One would think that applications of IR detectors in surveillance would be developed and well protected by the Drug Enforcement Agency, Office of National Drug Control Policy, and police organizations, lest criminals learn of their use and implement countermeasures. But executives we interviewed were surprisingly open about current applications, and system design needs. Despite the secrecy surrounding most police surveillance technology and sensors for drug interdiction, the users, designers, and researchers we contacted converged on a list of applications and recommendations which we believe to be comprehensive. As before, we base our findings on extensive interviews of systems designers, suppliers, end-users, trade associations, and researchers, who are listed in Appendix M.

We discuss in this section, as in previous ones, specific applications, followed by an identification of desirable characteristics in the design of relevant systems. We then analyze the market potential for IR detectors in surveillance, and particularly for MCT-based variants in particular. Finally, we discuss current suppliers, their niches, and specific systems for the surveillance market.

Applications. The aim of law enforcement surveillance is to uncover, observe, and convict criminals, to detect and verify specific unlawful activities, and to map out locations where those illegal activities are taking place, without the criminals' knowledge. Passive reconnaissance is the key to catching criminals "in the act," whether it is cocaine distillation in the jungle, or robbers fleeing into the woods. For this reason, infrared detectors have taken their place alongside other essential photonics equipment used by law enforcement agents such as searchlights, cameras, gyro-stabilized binoculars, and data-link video capabilities.

IR cameras have been extremely successful in two broad areas of surveillance: police law enforcement and counternarcotics surveillance. Both broad areas of application, described below, are very similar to military-style night imaging and aerial reconnaissance missions, with the systems used matching typically those designed for DoD.

In both varieties of application, officers mount forward looking infrared (Flir) cameras in gimbals, on helicopters if used for law enforcement, or on light aircraft if used for drug interdiction. IR cameras on airborne platforms can thermally profile persons or objects (ie. cars, tunnels, or underground stashes) on the ground, or survey large tracts of terrain up to about four miles in width.

Policemen have found Flirs helpful in a number of ways. Mounted on helicopters, Flirs can assist in criminal search missions by locating fleeing suspects at night or in adverse weather. Since the heat generated by a body differs from that of surrounding woods or foliage, fleeing criminals can be easily detected. One officer explained that during a downtown chase he had lost a suspect who had turned off his motor and lights, and concealed the car with a chamois cover. With an infrared detector, however, the officer picked-up the car by its hot engine and extremely hot tires, with a friction-created hot tread pattern leading to the concealed car. The suspect was found hiding inside the car. Another officer, using an IR detector, found a suspect hidden inside a metal shed because his body heated the wall of the shelter and could be seen from the outside. In night-time raids in which helicopters have been used, Flirs have been used to guide vehicles instead of spotlight, to keep criminals uncertain of the helicopter's location, and to offer elements of surprise.

Police officers at the Los Angeles Police Department told us that they can use IR detectors in several innovative ways because the high moisture content of the air in the region allows objects to warm up quickly, keeping good thermal records of recent events. For instance, officers have been able to see foot steps caused by the friction of running, left by subjects fleeing in the woods, across fields, across lots, etc. Cars also leave thermal tracks, caused by friction of the tires as they move.

Similarly, Flirs can be used to help locate lost or entrapped people, especially those in rough and remote areas. For instance, lost children can be picked out in a field, the woods, among foliage, among buildings, or in bad weather or darkness using helicopter-mounted Flirs. The same is possible, according to law enforcement officers, for Alzheimer's sufferers and elderly, who have been located using IR detectors. Unconscious people, whether trapped in shallow collapsed rubble or missing at night also can be located. Hikers and campers lost in remote areas could be spotted at night. In the worst case, shallow graves (up to about a foot in depth) can be located because a decomposing body generates excess heat for about 20 days after death. Deeper graves could be located using the dual IR/GPR style technique described in the section on remote sensing. Bodies floating down rivers have been found using Flirs mounted on helicopters which fly along the river.

Medical evacuation (medvac) teams, which use helicopters, have employed Flirs to help with night-time landings and low-level flights. When evacuating the sick in remote areas or victims who need to be flown great distances quickly, helicopters must often operate under adverse conditions and darkness. Obstructions can be imaged better and sooner using Flirs than spotlights. For instance, medvac helicopters have become entangled in elevated electrical wires which typically have black coatings and are hard to see with spotlights. The black coating, however, absorbs heat very well during the day, and is easily revealed with IR detectors.

Police and Coast Guard marine vessels and helicopters also have used Flirs to find survivors from maritime sinkings, capsizings, or crashes, at night or in adverse weather. A body, of course, is at least several degrees warmer than the surrounding water. Even for two to three days after a person has died in the water, core body temperature remains above the water's, so Flirs have been used to find drown victims as well.

Fourth, nighttime out-of-season hunters, fishermen, or poachers also have been found using Flirs. One officer said he recorded on videotape, from a helicopter, night-time IR films of fishermen throwing their tackle into the water and fleeing. Campers and squatters on restricted federal lands could be located at night by the heat of their fires or bodies.

For all these applications, night vision goggles would seem to be an obvious, and cheaper choice than Flirs, yet no airborne police unit uses them. This is because police helicopters fly typically through areas dotted with artificial light, especially if operating in populated areas, and night vision goggles would be saturate and produce no image when exposed to even low lights. Night vision goggles are better suited for all-dark applications where there is no chance of encountering strong lights. An officer we spoke with used night vision goggles during a night-time sting operation on a rural home, but the suspect fled through his back porch undetected because a 60-watt bulb had been on and blinded the night vision goggles. For this reason, all police departments prefer Flirs over night vision goggles and earlier light intensification equipment, despite the added expense.

Police officers on the ground, however, use night vision goggles or image intensifiers. Police officer in New York City, for instance, use the goggles to stalk criminals and retrieve homeless people in subways, tunnels, and pitch-black alleyways. Police use the goggles to approach locales where they do not want to use flashlights. Units cost about $4,500 to $6,700, and officers we contacted were content to remain with those systems now in use, rather than upgrade to Gen III systems which possess higher technology.

A recent surveillance application is in police helicopters flying around buildings which are on fire, to view the walls with a thermal imager, in order to find which areas are hottest and where the fire is spreading the fastest. Such devices can be used to assess the extent of a fire before firemen step foot inside. Except for one effort at the Naval Research Lab where researchers investigated the use of man-portable Flirs to see during electrical and gas fires, however, we believe that no fire departments are currently using Flirs.

The US Customs and the Bureau of Naturalization has used infrared detectors for border security and perimeter control. Border security prevents aliens from emigrating to the US, whereas perimeter control protects sensitive bases (most often military) from intrusion. Properly equipped air platforms can provide the edge against intruders. Large areas can be scrutinized for trespassers, to determine flow patterns of these trespassers, to establish choke points, and for command and control during the actual capture. For example, McAllen Border Patrol Air Operations helicopters rely on Flirs to locate illegal aliens, and then shine a spotlight on the aliens during capture. For military bases, moreover, as well as corporations with large sensitive areas, IR spectrum surveillance is their method of choice for perimeter control.

The second general area in which Flirs have been used extensively is drug interdiction. Local police departments, as well as the Drug Enforcement Agency (DEA) and Office of National Drug Control Policy (ONDCP) have placed Flirs on light aircraft in the US, South America, the Caribbean, and the Pacific for detection of marijuana. Originally, multi-spectral imagery from space satellites such as Landsat and SPOT were used to identify crop types (cannabis, coca, opium), chemical effluents, and processing sites (such as their drying stacks, processing pits, and chemically stressed foliage areas). As early as 1974, multi-spectral imagery provided data useful for the identification of narcotic crops and their growth stage. In these cases, multi-spectral systems searched for the unique spectral profile of the drug crops.

More recently, researchers have been able to use Flirs in light aerial overflights to identify outdoor marijuana plants because the cannabis plant requires more watering than other tropical plants, and the excess moisture absorbs more heat into the soil. The soil temperature is noticeably warmer when it has been watered to the level necessary for marijuana. In response, many marijuana growers in the US have moved their operations indoors to avoid detection from overflights, but the indoor lights necessary for growth produce excess heat which can be readily seen by infrared imagers. Growing houses in atriums and plastic opaque greenhouses are the easiest indoor structures to find, according to officials. Even if insulating heat panels are installed, Flirs can still snuff out indoor marijuana growth because heat still seeps through, aided by the high humidity environment which retains the heat. Likewise, the heat of cocaine and opium distilleries can be detected using flirs.

The Coast Guard and Customs Service use Flirs to intercept high-speed boats which dash in for quick deliveries, often under the cloak of darkness. Similarly, small aircraft which attempt to fly underneath surveillance radar at night have been quickly spotted by patrol aircraft equipped with Flirs. In those missions, planes such as the Coast Guard's Hu-25 Falcons are equipped with radar and Flirs. Radar is used for long-range reconnaissance, whereas Flirs are used for close-range navigation and tracking.

Specifically, combat air patrol craft identify suspicious aircraft, for instance, that have not filed a flight plan with the FAA, and are headed toward the US from Latin America or the Caribbean. Suspicion increases if they fly low and do not transmit an Identification Friend or Foe code. In order to intercept the suspect without being spotted, radar identifies suspected aircraft, and guides law enforcers to the suspect. The Flir then detects heat emissions from the suspect's airplane's engines, giving early information on the suspect, specifically the type of aircraft being flown. Flirs are generally activated when patrol aircraft are about six miles away from a suspect, and at 1,000 to 1,500 ft, the Flir could be used to read the suspect's identification number. The Flir could record on videotape as suspects drop bags of contraband out of their aircraft. In many instances, those videotapes have been sent to local police authorities to aid in a surface search. The infrared tape also records the intercept sequence for use in court.

A use proposed for the dual-band IR detector designed at the Lawrence Livermore National Labs, described in the section on remote sensing, is to locate underground epicenters of smuggling and drug production. For instance, buried foundations, walls and trenches, roof tops disguised by jungle canopies, and covered containers used for the storage of contraband could be located. Another future application could be the detection of chemical byproducts discarded during coca and opium processing and released into nearby soil or waterways. Such chemicals would change the emissivity or rate of heat absorption/loss in soil or water, and could be noticed by thermal imagers. Another proposed narcotics application is the use of backscatter gas absorption detectors, also described in the remote sensing section, to detect specific gases released by marijuana, coca, or opium distillation plants.

To our knowledge, thermal imagers are not being used in any kind of contraband detection where non-intrusive searches are conducted of cargoes, vehicles, and other platforms. X-rays are the undisputed technique of choice for contraband searches not requiring wide area coverage, because they can penetrate cargo, rather than imaging only the surface as IR detectors do.

Likewise, since the strength of IR detectors lies in their ability to reconnoiter passively, catching robbers "in the act" without their knowledge, it is unlikely that IR detectors would be useful in the potential application often cited by IR firms seeking high-volume applications: night-time surveillance of warehouses, commercial spaces, factories, lots, garages, shipyards, and, eventually, individual houses. All the surveillance camera executives we contacted explained that most criminals are deterred by bright lighting, and that IR detectors, which require darkness, have no deterrence value. IR detectors could be successful in helping catch criminals in the act of committing property crimes, but would not stop crimes before they happened, which is the primary aim of the law enforcement agencies. Likewise, if properties were darkened for IR detectors, criminals would presumably approach with flashlights, which would blind the infrared cameras stationed to detect them. For these reasons, we are pessimistic about claims of potentially widespread civilian surveillance applications for IR cameras.

Nonetheless, one surveillance executive wrote that "when a security professional spends several nights in a warehouse parking lot hoping to identify suspected drug dealers, he or she is coming face-to-face with the one factor that has frustrated the security and law enforcement communities for centuries: the cover of darkness that shields nighttime crime."[52] Although many producers of infrared detectors anticipate their cameras being used in property surveillance, we remain doubtful about the eventual market.

The Counter-Drug Technology Assessment Center, which funds innovative technologies for the President's Office of National Drug Control Policy, is committed to funding IR technologies, according to officers we contacted. In the 1992 Broad Area Announcement, the Center sought proposals for wide area surveillance to "apply technologies to monitor and detect the growth, processing, shipment, and distribution of illegal narcotics. Projects could include, but not be limited to, applications of radar, IR, UV, and optical sensors, tagging devices, communications, command and control, data management, and information exploitation networks, and instrumented ranges and testbeds to support development and testing of wide area surveillance technologies."

An auxiliary application, which does not fit either grouping above, would use infrared cameras to check passengers boarding airplanes for plastic guns. These are weapons not yet perfected, but widely anticipated by counter-terrorist officers. In this application, the density of the plastic would block heat emanating from the skin. The IR market for airport security, of course, would be very modest, and there is no telling if plastic guns will become available.

Systems Design. Most Flirs deployed by the police and counternarcotics agents are either helicopter- or light airplane-mounted systems, and resemble military-style reconnaissance units. A system weighs typically about 35 pounds, including the cryogenics, camera, VCR to record images, and some elementary processing electronics. Most airborne IR detectors currently deployed by US law enforcement personnel provide two fixed fields of view: a wide field for detection and tracking (30 degrees field of view), and a narrow field for recognition (5-8 degrees).

Police officers suggested that car-mounted infrared cameras would also be desirable, but suppliers are focused on the airborne market (presumably because there are more value-added items in aerial mounted systems). The standard four minute cool-down period for cooled IR detectors, moreover, during which the detector's cryogenics drops the detector suite to liquid nitrogen temperature, is too long for car-mounted applications. In car-mounted scenarios, for example, a suspect would run off into the woods or drive into a field at night, and the detector would need to be immediately flipped on to continue pursuit. Thermo-electrically cooled

[52] Jeff Frank, "Out of the Darkness," Security Management (August 1991) pp. 45-47.

detectors are a likely solution.

A major area of innovation in the design of IR surveillance systems is the integration of more sophisticated "target recognition" software to pick out human body temperatures and shapes autonomously, or to identify particular cannabis temperature differentials by comparison with surrounding plants. In this manner, large areas could be scanned automatically by a Flir, with some sort of alarm alerting the helicopter or airplane crew of areas of interest.

A second major area of innovation is that single payload gimbals are being replaced by multiple role sensor assemblies, capable of two and even three waveband imaging, target designation, and illumination. The ability to provide these multi-function sensor pods and integrate, analyze, and store the resultant imagery and data will be a necessary requisite for future IR imaging systems.

Radiometric properties, by comparison with other areas of application, offer little advantage to surveillance instruments. Resolution, sensitivity, and dependable calibration are more important technical considerations.

Market Analysis. The surveillance market is likely, by all indications, to remain steady in growth during the next decade. Since Flirs are only employed by about 40 percent of the US law enforcement agencies with airborne equipment, and a handful of new applications are opening up, there is room for steady market growth.

The consensus is that Flirs are essential to many law enforcement and drug interdiction operations. The Airborne Law Enforcement Association (ALE) reported in 1992, based on responses from 152 of its 268 member agencies, that airborne photonics helped seize over $4 billion in contraband, found 13,000 escapees or bailouts, 3,000 lost or entrapped people, and supported more than 38,000 arrests. The only photonics technologies used more pervasively than Flirs (which were used by 42 percent of ALE's member agencies in 1992) were LORAN Navigation Systems (65 percent), Floodlights (59 percent) and Public Address (PA) Systems (48 percent).

In Table 12 below, an industry executive and a surveillance officer rated several photonics techniques employed by officers "from one to ten" (10 meaning the highest level of usefulness) in terms of effectiveness in varying areas of application, finding that IR detectors were as useful as routine equipment like spotlights and visible cameras[53]:

**Table 12. Rating the Value of Various Photonics Technologies in Surveillance**

| Device | Search and Rescue | Border Patrol | Drug Enforcement | Anti-Terrorism[54] | Maritime | Law Enforcement |
|---|---|---|---|---|---|---|
| Visible Camera | 4 | 3 | 10 | 6 | 7 | 6 |
| IR Camera | 6 | 9 | 6 | 9 | 7 | 8 |
| Searchlight | 10 | 8 | 5 | 6 | 5 | 10 |
| IR Illumination[55] | 2 | 4 | 5 | 8 | 1 | 4 |
| Long Rangefinders and Designators | 0 | 1 | 3 | 5 | 3 | 0 |
| Radar | 6 | 3 | 9 | 1 | 10 | 3 |

MCT-based detectors are competitive with InSb- and PtSi- based detectors in the surveillance market, with the major market drivers being cost, performance, and resolution. The range of choice in wavelength does not appear to be an issue in surveillance, since scanning devices operating in both the 3-5 and 8-12 micron windows have been used. Systems which operate in the LWIR offer a longer range and often better responsivity. Officers had no spectral preference, but counternarcotics agents, who often collect aerial data from about 6,000 feet altitude, preferred the MCT-based detectors for their better resolution over long distances. For either style of application, less sophisticated detectors (based on lead salts or germanium) have never been considered because of the resolution and long focal lengths required for helicopter or light plane overflights.

[53] David Aikens and William Young, "Airborne Infrared and Visible Sensors Used for Law Enforcement and Drug Interdiction," SPIE Conference on Surveillance 1991, 12 pgs.

[54] A very limited area of application for IR detectors in which terrorist hangouts are remotely sensed, and in which drawn firearms are thermally detected in a crowd.

[55] In IR illumination, an IR spotlight, which is invisible to the human eye, illuminates a limited area which is imaged with an IR camera

Several major defense contractors have tried in the past to penetrate the surveillance market, but their Flir systems started at about $750,000 in a market which is only willing to pay about $125,000 for a camera, simple processing electronics, a VCR, and gimbal mounting hardware. They had been trying to sell military-style Flirs, without much concession to the unique needs of end-users in the surveillance market.

Staring systems which use focal plane arrays are finding more surveillance applications as their prices fall, but are not always necessary for many applications. IRFPAs have found more use mounted in gimbals on the underside of a helicopters than on the ground. This limitation will probably change in the near future as IRFPAs shrink in price, size, and cooling requirements, and improve in their ability to stay calibrated, according to industry executives.

Advanced automated Flirs for aerial reconnaissance will also open up new markets. One firm we contacted, for instance, fuses a Flir, a scanning IR detector, and a visible-light camera into a sophisticated tracking system for aerial reconnaissance. The scanning camera images broad areas of terrain, searching for targets which have been pre-programmed, and cues the FLIR to hone in on areas of interest.

We encountered two barriers to the widespread use of Flirs in law enforcement and counternarcotics. First, non-intrusive examination of homes, people, and activities using IR detectors has major implications for civil liberties and the right to privacy. The DEA, which has been relying on remote thermal imaging of homes to detect indoor marijuana growth, has come increasingly under fire for violating the US Constitution's Fourth Amendment guarantee of protection from unreasonable search and seizure. This argument was rejected in a July 1992 decision by a US District Court in Pennsylvania. The court ruled that people retain no privacy interest in the heat escaping from their homes, even in this case, where the suspect had taken elaborate precautions to contain the heat by boarding up windows. The court emphasized that the thermal imager did not penetrate the house with rays or beams, which would be unlawful, and compared passive IR sensing with the lawful use of a trained dog to sniff baggage for drugs. In the long run, however, more legal challenges are bound to surface in the US in opposition to technologies, such as IR detectors, which can penetrate private buildings. In any case, the law has not kept pace with advancements in photonics technology, and more legal challenges to IR surveillance are bound to occur.

A second barrier is that budgets for counternarcotics operations are volatile. As goes the Administration's priorities on the "war on drugs," so goes DEA and the ONDCP's budgets. Although both offices have seen more than a doubling of their respective offices from 1991-1993, indications are that their budgets will be dwindling in the years to come.

In summary, the surveillance market for infrared detectors should remain consistent at about 5 percent annual growth, as more police precincts and counternarcotics teams acquire Flirs.

Law enforcement agents are very familiar with infrared technology, prize it for its strength in almost all varieties of night-time operations, and should continue to invest in the technology as innovations such as IRFPAs become more broadly available and affordable. Based on interviews, we estimate that if IRFPA-based cameras reached the target price of $125,000 per unit, the market may approach, 450 units annually in police law enforcement, and another 200 for use in counternarcotics. The market could total about $80 million when the market matures in three to four more years, and as more precincts become convinced of the utility of Flirs.

## Transportation

Three transportation applications potentially could use sophisticated infrared detectors, and their volumes would dwarf those of all other proposed applications. Virtually all military and commercial IR producers are interested in pursuing these applications, and some are well on the way toward actual products:

- As night driving aids in cars, trucks, vans, and other vehicles, infrared detectors could either catch on like car tapedecks, creating a market reaching $100 million annually, or fizzle out like Honda's ill-received four wheel steering option.
- As components in intelligent vehicles highway systems (IVHS) worldwide, IR detectors could realize a $40 million annual market.
- As enhanced vision systems for airplanes, helicopters, and sea vessels, IR detectors will likely realize a $200 million annual market in about five years.

Each prospective market is discussed in the following sections. The executives interviewed to obtain this information are listed in Appendix N.

Driver's Nighttime Vision Aids. Producers of all types of infrared detectors are seeking to develop systems to aid drivers of vehicles with night vision displays. Such aids would enhance vision not only during night-time, but could also peer through rain, fog, snow, and smoke better than the human eye. With the potential to sell 100,000 systems annually at $1,000 apiece, the promise of a $100 million annual market has spurred great interest among IR manufacturers.

Almost all producers and automobile manufacturers agree on the general system design for a driver's vision enhancer. A thermal imager would be placed either in the center of a car's roof or under a raised area in the hood (which would look like an airscoop), from where it would pick up a clear night-time image. An imaging range of about 400 meters would be required. Sensitivity of about 0.1°C would satisfy consumers. A 28 degree field of view is desired. The night vision camera would swivel to two positions: forward, for normal driving, and directly backwards. The driver would view the image on a small camera console located just below the dashboard near the center of the driving compartment (where the gauges are usually housed), angled towards the driver. The camera would not be a mini-CRT, but rather a flat-panel display measuring about 5" X 7". Sophisticated flat-panel displays which are only an inch or two thick are preferred by several car manufacturers, but they will not be available for three or four years at the assumed cost of $150. A touchtone panel on the camera would allow the driver to change the detector's angle like a mirror's. The expected mean time to failure for the entire systems has been estimated by various executives to be anywhere from three to eight years. Researchers have also experimented with projecting the infrared image onto a heads-up display on the windshield, but this seems prohibitively expensive.

The most innovative aspect of a driver's vision enhancement system is neither performance, since military-style detectors have far surpassed the required 0.1 NETD sensitivity, nor resolution, since vide-size arrays are possible with all IR materials, nor even the speed of image update, since almost any material images fast enough to fulfill the specifications. Rather, it is the low cost proposed for the driver's vision enhancement system that is the primary challenge. The entire night vision set-up would be installed by manufacturers as an option on automobiles at a cost of about $1,000. That means that the producer of the units could realize a price of only about $700, and eventually closer to $500.

Several automobile manufacturers are enthusiastic about offering night vision aids as an option on their cars. The team with by far the most experience comprises General Motors, GM's Hughes affiliate, and Texas Instruments. The GM team proposes to have systems ready for installation on Cadillacs by 1995 or 1996. Outsiders doubt a night vision option will be ready before 1997, and more likely not until 1998. The plan is for Texas Instruments to build the uncooled ferro-electric detector, which Hughes will integrate into a complete system and then will be distributed by General Motors. Hughes' Santa Barbara Research Center is a potential second source of the detector, utilizing the microbolometer technology it recently licensed from Honeywell and Alliant Techsystems. (Both technologies are described more extensively in a later section on uncooled IR detectors).

The GM team has been exploring night-time vision concepts since 1986, with serious research underway since about 1990. Six prototypes are currently in operation in US cities. GM is also conducting studies to determine the size of target markets, with early indications that truck drivers, the elderly, and "red-eye drivers" such as salesmen and long-distance or night-time commuters would find such a system handy. GM predicts it could sell at least 20,000 systems annually from-the very start.

By contrast, Ford and Chrysler are reputed to be investigating night vision systems only to keep up with General Motors, but both IR industry, and automobile industry executives doubt the latter two will have systems out in time to match GM. BMW is the only European company known to be investigating night vision aids, and the company is keeping close wraps on its plan. BMW is said to be investigating a system using two infrared cameras and a video camera that have been mounted on the car's roof. The infrared cameras sense minute differences in the temperature on the road's surface to create their picture, which, combined with the video image. shows the driver where the car is in relation to the striped white line. Several Japanese automobile manufacturers, especially Mitsubishi, are said to be exploring PtSi CCDs as options on their cars; the Japanese market may be much more open to such systems because Japanese automakers already offer a popular commercial navigation system for passenger vehicles (which does not operate with IR frequencies).

Whether IR night vision systems will catch on with US consumers is a matter of heated debate among automobile manufacturers. The team of GM/Hughes/TI is betting heavily on its success; TI in particular has already invested $15 million in a new production facility. The other automobile manufacturers have been more cautious. Certainly, the potential exists for a widespread market; 55 percent of traffic fatalities occur after dark, even though only 28 percent of driving takes place then. Safety officials say one of the biggest problems is that people tend to "overdrive" their headlights, meaning they go faster than warranted by the distance illuminated. By the time an obstacle comes into view, there is not enough distance to stop. Headlights can typically see a person in dark clothes at 300 feet. Driver's vision enhancers, however, can make that person visible 1,600 feet away -- more than five times the distance.
But except for the GM market studies said to be completed this year, there is no empirical data on how effectively night-vision diving aids address the needs of drivers.

The Department of Defense, on the other hand, is convinced that infrared detectors should be integrated into night vision equipment for military vehicles and is already funding development programs for that purpose. The Army's Communications- Electronic Command (CECOM) let an RFP in March 1993 for the Driver's Vision Enhancer (DVE) program, and was in source selection in April of 1993. The DVE's program manager, Col. Dave Michlik, explained that armored vehicles, which are already equipped with night vision equipment, were able to advance at night during Operation Desert Storm, but that their support vehicles lagged because they had no comparable capability. The Army potentially could put thousands of IR imagers into their support vehicles.

What is remarkable about the DVE program is that the Army has not set any "challenging" design parameters other than the unit price. The winning bid will probably be under $2,000 per unit, according to industry officials. The DVE thus would resemble its cheaper commercial versions: The FOV would be 40 degrees horizontally, and 20 degrees vertically, spatial resolution would be 2.5 milliradians, start-up time would be no more than five minutes, and units are to operate a minimum of 12.5 hours without interruption. These parameters are all easily achievable using existing technologies; price is the challenge. The type of IR material employed, the type of TV screen utilized, and the positioning of the cameras are all left to bidders. In Phase I of the program, to be awarded during the first half of 1993, two manufacturers will be selected for the production of twenty-five prototypes each. In Phase II, expected to start 22 months after the start of Phase I, a sole winner will complete the system's development. Full production is not expected to begin before the end of the decade.

Nearly everyone we interviewed said that TI is, of course, the leading contender for one of the two prototype developers. TI's ferro-electric technology is far ahead of the other two firms working on uncooled detectors, Alliant and Honeywell. According to TI executives, the company will offer a spruced up mil-spec version of the commercial night vision system it is developing for GM and Hughes. Alliant/Honeywell is said to have entered a bid based on microbolometer detectors. Magnavox is said to have entered the competition as well, presumably with MCT-based detectors. SBRC also entered the competition, presumably with either a variation of its MWIR MCT-based Time-Delayed Integration detector it is developing for the Thermal Weapon Sight, or with the microbolometer technology it recently leased from Alliant/Honeywell.

The successful bidder for the DVE program would be in a good position to build a high-volume facility dedicated to manufacturing IR detectors cheaply and efficiently, and would certainly have an advantage in penetrating the commercial market.

The Army's CECOM has also been demonstrating various IR imagers at trade shows, most recently at the US Council for Automotive Research's Automotive Technology Exposition. At that particular expo, the Night Vision and Electronic Sensors Directorate's chief scientist, James Ratches, contrasted various IR technologies for automotive night vision, including InSb, PtSi, MCT, and other uncooled detectors. He also discussed various display technologies developed by CECOM which may help in designing a complete night vision system, including flat panel displays and other components. He demonstrated the night-time visibility offered by IR detectors by showing thermal pictures of cars ahead on a highway, and from an airport landing strip. Although there is no indication that the Army will help offset commercial developmental programs, it is clear that Army officials recognize the dual-use potential for IR detectors as driver's vision enhancers.

<u>Intelligent Vehicle Highway System</u>. A second area of proposed application for infrared detectors in transportation is in the intelligent vehicle highway systems (IVHS). The IVHS is a multi-billion dollar federal program managed by the Department of Transportation with the potential to become a large new industry in the last part of this century and the first two decades of next. The program has the potential to make driving automobiles and other ground vehicles significantly safer, to reduce congestion, and to incubate high-technologies that could find market in the US, Japan, and several European countries. It is a broadly based program, bringing together many advanced components, IR included, which for the most part are already technically feasible and available. Most technologies proposed for the IVHS in fact were developed by the Department of Defense, such as GPS receivers, complex vehicle location "command and control" systems, collision avoidance systems, and navigation systems. IVHS-like technologies are also under investigation for other modes of transportation, such as railroads, ships, and commercial aircraft. IVHS technologies are listed and described in table 13.

**Table 13. Major Areas of IVHS Technologies**

| Area | Description | Possible IR Uses |
|---|---|---|
| Advanced Traffic Management Systems (ATMS) | On-and Off-ramp metering, signal control, and other traffic functions. Also will provide the basic information for many of the other IVHS functions. More sophisticated versions of ATMS may be used for prediction and control of traffic congestion by providing alternate routings, etc. | Infrared beacons and receivers |
| Advanced Traveler Information Systems (ATIS) | Will provide traveler with navigational tools, weather and road conditions, locations of accidents or trouble spots, etc. An on-board navigation system is a major feature of this system. Could be used for pre-trip planning at a home computer terminal. | Infrared beacons and receivers |
| Advanced Vehicle Control Systems (AVCS) | For Improving safety and vehicle control. Collision avoidance systems will be a primary feature, utilizing microwave, millimeter wave, and optical approaches. Smart cruise-control systems which maintain safe distances and speed between vehicles also is part of this system. | Collision avoidance |
| Commercial Vehicle Operations (CVO) | Versions of the above systems for trucks, buses, emergency vehicles, and taxis. | Nighttime vision and collision avoidance for commercial vehicles |
| Advanced Public Transportation Systems (APTS) | Versions of the above designed for high-occupancy vehicles, such as buses, vans, and car pools. "Smart Cards" could be used to pay tolls. | Nighttime vision and collision avoidance for high-occupancy vehicles. |

Source: The Intelligent Vehicle Highway System & Related Programs -- A Technical/ Economic Analysis, Business Communications Company, El Prado, NM, report GB-162.

IVHS has received substantial funding, ensuring that at least some system will eventually hit the roads. The IVHS program in the US is a $659 million, six year program (1992-1997) funded through the Intermodal Surface Transportation Efficiency Act of 1991. In addition, the Congress has been supplementing R&D funds annually. The amount of the 1993 baseline is $30 million per year, to be adjusted for inflation in future fiscal years. Moreover, IVHS funding was included in the "Rebuild America" initiative submitted by President Clinton. If passed by Congress, it would provide an additional $70 million annually starting in FY 1994, growing to $100 million by 1997. Additionally, the largest source of funding is individual private companies developing products to sell to consumers and public agencies. The size of this investment, of course, is unknown.

How extensively would IR detectors be used in IVHS? In the near-term, private companies with fleets of expensive vehicles, such as buses, trains, ships, and trucks, may acquire their own autonomous IVHS equipment, including IR detectors. These companies believe they cannot wait over a decade for the federal program to produce operational results. For example, Japan's high-speed railways are already using Mitsubishi PtSi infrared cameras in their trains' noses for night and bad weather vision. US railroads also are actively pursuing IVHS-type technologies for rail applications, including IR detectors. It is fairly certain, according to executives we contacted, that IR cameras could be put on trains within the next five years.

But the true high-priority systems such as Advanced Traffic Management Systems and Advanced Traveler Information Systems, would not use sophisticated, scanning or staring IR detectors. Infrared beacons will almost certainly find widespread application, but not sophisticated IR detectors.

And most privately implemented IVHS systems are not IR-related. For instance, Greyhound Bus Company announced in the Spring of 1992 that it was installing a Vehicular On-Board Radar system in 2,400 of its buses -- a $5 million program. Likewise, many trucks, buses, emergency vehicles, and taxis are using navigation systems and two-way radio links with dispatch carriers. Automated Vehicle Identification systems are already in use for automatic toll collection.

In short, the most likely form of IVHS, which would identify the location of vehicles on roads and help direct traffic, or give the fastest route to a destination, or warn of slowed traffic ahead, would use IR frequencies, but not sophisticated IR detectors. Infrared frequencies offer two advantages to IVHS system designers: First, IR bands are not as complexly allocated and licensed as radio frequencies; and, secondly, IR energy dissipates in a short distance, by contrast with radio- and microwaves. In Siemen's Ali-Scout system, for example, which is representative of the multi-purpose systems available, each vehicle would have an IR receiver and transmitter operating in either the SWIR or near IR (about 950-850 nm). Beacons stationed nominally every half mile along the highway would also transmit and receive IR signals. Every car's IR transmitter would have a unique signature. The communication between cars, roadside beacons, and a remotely located central computer would allow users to compute the fastest route to a destination, pay tolls automatically, determine their exact position, etc. Riders could be located anywhere along the highway system, and would be able to navigate anywhere with computer guidance.

Ali-scout type systems require only primitive infrared detectors and transmitters. A row of about ten LEDs would be linked together to form the transmitter, and IR detectors would be more radio-style systems than focal plane arrays. Roadside beacons would not be *imaging* cars passing by; they would be picking up their IR signatures. The IR beacon/receiver portion of the Ali-scout or related systems would be worth about $15 million annually. Although derivatives of military IR detectors could be used for this, advanced focal plane arrays are certainly out of the running.

Collision avoidance systems, on the other hand, provide a market for sophisticated IR detectors. They are a medium priority for IVHS planners. Most likely, cars would be equipped with simple "target recognition" systems based on either microwave, millimeter, optical, or IR devices. The market could be worth about $5 million annually. If night vision equipment were to become standard in cars, the IR images could be analyzed by an on-board processor to determine if a collision were imminent. But the mid-term market is in trains, buses, trucks, ships, etc. whose operators could more easily afford such expensive systems.

Will IVHS happen, especially with technologies which employ IR? Most executives we contacted believed that at least the near- and mid-term programs will be implemented. That would include the Ali-Scout type systems with their rudimentary IR technology, and collision avoidance technologies for trains, ships, trucks and other public transport vehicles. Longer-term IVHS programs, especially ones requiring extensive infrastructural construction, are more tenuous; that includes collision avoidance systems for passenger cars. Although almost all IVHS systems are still in formative stages, all indications are that the federal and state governments will move ahead with IVHS systems, several components of which should employ IR detectors. In the final analysis, IVHS is a futuristic highway travel system more responsive to politics than to economics. Our recommendation is to focus on private companies to developing their own collision avoidance and enhanced vision systems, like those on Japan's trains, in the mid-term, and to anticipate conservative IVHS expenditures only towards the end of the decade.

<u>Enhanced Visibility Systems for Commercial Aircraft</u>. The Enhanced Vision System (EVS) is a major new technology that could bring large numbers of IR detectors into commercial transport aircraft. These on-board sensors would reduce the number of flight cancellations, diversions, and delays caused by inclement weather at certain airports. Two technologies are under investigation for the EVS: millimeter wave (MMW) radar, and conventional military-style Flirs. Either, or

even both sensors, would be mounted onto the fuselage centerline of aircraft and would give commercial pilots real-time images through a Heads-Up-Display (HUD).

Air carriers are interested in installing synthetic vision systems (SVS), as they are called by the Federal Aviation Administration (FAA), or enhanced vision systems (EVS), as the airlines call them, because they would enable pilots to land in poorer visibility than currently allowed. That would reduce landing delays, which would increase profit margins. Likewise, commercial airlines would be able to land at smaller airports which are normally shut-down when weather is poor. Specifically, the goal is to allow planes equipped for Category 1 landing operations (2,600 feet of runway visual range) to land in challenging Category 3A conditions (defined as 700 ft. runway visual range and 50 ft. decision height); the latter conditions are common at most suburban airports.

Aerospace companies have been experimenting with enhanced vision systems for the past four years, and systems could be deployed in commercial aircraft within another three to four years. EVS is a component of a larger "enhanced situational awareness system" (ESAS) which has been proposed for commercial flights, and would integrate sensors usually reserved for the military. The ESAS would incorporate enhanced vision for approach, landing, and taxiing and takeoff, as well as improved weather radar, clear air/wake turbulence detection, predictive wind shear capability, runway incursion monitoring, and improved techniques for avoiding flight into terrain. A heads-up display would integrate all the data. IR or radar assisted EVS would be the first sensors integrated into such a system which would have an open architecture for future add-ons. Airlines do not need to purchase entire ESAS systems; with tight budgets, they may opt for the essential components, such as IR or MMW radar imagers. The two major efforts underway to assess SVS technologies are a joint FAA/ Defense Department/ Industry Technology Demonstration Program, and aerospace-industry supported research at the Maryland Advanced Development Laboratory. The goal of both programs is to assess both millimeter wave systems and IR FLIRs.

The $14.8 million FAA/DoD/Industry research team mounted a GEC Avionics HUD integrated with a Kodak MWIR PtSi FLIR on several planes. The same HUD was integrated with a Lear Astronics 34-Ghz and 94-Ghz radar system for comparison. All three systems were tested simultaneously during flights. Researchers preferred the 35-Ghz millimeter wave radar, which could image a runway from an altitude of about 350 feet on the glideslope. Their subjective preference was for the radar set-up, rather than the MWIR FLIRs, because MWR offered better resolution, even if the radar had poor resolution and did not adequately estimate the size of objects in the field of view. Members of the research team opined that LWIR infrared detectors may well have penetrated fog and rain better than the MWIR variety they tested.

The Maryland Advanced Development Laboratory (MADL), used a MWIR Mitsubishi Thermal Imaging camera, utilizing PtSi-based detectors, combined with three HUDS: one produced by Sextant, one by Kaiser and integrated by Rockwell Collins, and one by GEC-Avionics flown on the F-16 Lantirn. They found that the IR camera extended the pilot's visibility to nine miles under marginal visual conditions. When fog lowered the visibility to 0.4 mi, the IR detector allowed the pilot to see out to three miles, or seven and half times what could be seen by the naked eye.[56] Researchers also found that although MMW Radar is less affected by adverse weather than IR signals, it does not give nearly as good resolution as IR. Visible moisture in fog and rain scatter light and absorb IR radiation, but the IR detectors still outperformed radar.

Which technology will prevail? For now, both IR and MMW Radar have advocates in the FAA and aerospace industry. To its credit, MWR has better penetration in fog, and degrades less than infrared. But its range is limited, it offers inferior resolution compared with sophisticated IR detectors, and it offers poorer image quality. Objects also appear significantly different when viewed with MWR instead of the naked eye, and this may discourage pilots from relying on MWR. Infrared FLIRs, on the other hand, offers higher resolution, greater range, and more recognizable images. Several commercial producers said MCT-based arrays, which have not been tried so far in tests, would have offered improved performance over the radar systems, especially ones operating in the LWIR. A likely future step would be for MCT-based detector firms to promote their technologies over the PtSi detectors now being tested. What is certain is that MMW radar has been used more extensively than FLIRs, and firms are more experienced in integrating them into HUDs. One executive we interviewed said FLIRs hadn't been affordable commercially until about five years ago, when breakthroughs in cooling technologies made them available.

The airlines we contacted said that complete systems for EVS would need to cost under $500,000, depending on how much the FAA allows visibility minimums to be lowered. Compared with an Autoland System, which would be the only alternative for Category One aircraft seeking to land in Category 3A conditions, the EVS could be a "real bargain" according to industry officials.

The only hurdles are FAA certification and actually integrating IR sensors into HUDs for commercial aircraft, processes which should take no more than three or four years. IR technology is already sufficient for the job. Northwest Airlines contends that systems could be FAA-approved within a year and a half, but almost everyone else in the industry judged this to be too optimistic. Northwest and United Airlines have both been contributing to the two current studies, and would be the first airlines interested in such systems. The French domestic airline,

[56] Bruce Nordwall, "HUD With IR System Extends Pilot Vision" Aviation Week and Space Technology (February 22, 1993) pp. 62-63.

Air Inter, and Alaska Airlines also already have HUDs in their aircraft, so either FLIRs or MMW radar would be likely additions once the technology becomes available.

The market could be quite large because the majority of airports in the US are liable to shut down or delay flights during conditions which could be overcome with EVS equipment. There are only about 35 US airports at which planes equipped with EVS would not benefit, such as Los Angeles International, Chicago O'Hare and John F. Kennedy International in NY. EVS-equipped lanes would benefit planes landing at about 1,100 smaller airports. Many of these locations must cease landing operations several times a year for weather-related reduced visibility, interrupting airline, cargo, and corporate flight schedules.

Not only is the market ample, but there is already substantial movement towards installing EVS into commercial aircraft. Northwest Airlines is evaluating HUD systems being offered by Sextant Avionique of France, GEC Avionics of the UK, and Rockwell-Collins teamed with Kaiser Electronics. Hughes Aircraft's Flight Dynamics, Inc. subsidiary, which has head-up guidance systems on Alaska Airlines' Boeing 727s, was not picked by Northwest. Hughes has since sold its EVS operations to Kaiser, which is negotiating with Alaska Airlines to install similar systems on its fleet of 737s. United Airlines has also expressed interest in purchasing the systems, and has contributed to both current research teams.

Several other companies are teamed and jockeying for position in the emerging market. Honeywell Commercial Flight Systems Group is allied with Westinghouse and GEC Avionics to develop EVS systems. Westinghouse is exploring the sensor technologies for the team, using both 3-5 and 8-12 micron varieties of IR detectors. Kodak has provided the 3-5 micron PtSi detector. Also, Boeing is reportedly going after the larger concept of ESAS with several avionics companies. Likewise, Rockwell-Collins has teamed with Kaiser Electronics and Kodak. Kodak provides the team with PtSi-based CCDs which operate in the MWIR. Sextant Avionique is also working on a commercial EVS system, but has more experience with developing commercial HUDs than with assessing sensors; they are not teamed with any IR sensor companies. Finally, Kaiser is also pursuing EVS with Boeing along with its Flight Dynamics subsidiary and Smiths Industries in the UK.

We estimate that about 400 systems could be sold annually during the next decade, reaching a market worth $200 million annually. Only about a fifth of the total system cost would be attributable to IR detectors, however. Whereas the more complex ESAS systems proposed by several manufacturers may never fly because of cost, simpler EVS systems which integrate IR or MMW radar are certainly the way commercial airlines will go in about four years. LWIR MCT-based detectors, which made their name in long distance imaging applications where sensitivity was crucial, would be a natural for EVS. Kodak appears to have entered the market before other IR detector producers, and is promoting inferior PtSi technology which operates in an IR band (3-5 microns) that is not ideal for EVS, and which produces images only slowly.

Several airline executives understood this and suggested LWIR MCT-based detectors would enhance sensitivity and stretch the distance of sight, while perhaps sacrificing some of the resolution offered by Kodak's PtSi detector. If MCT-based detectors were introduced, they would likely capture a large share of this market.

## Part Three

## Conclusions

In this section, we analyze the differences between IR sensors now being developed for the US armed forces and those which could succeed in dual-use markets, estimate the size of the markets awaiting manufacturers of commercial IR systems with suitable characteristics, describe a prioritized federal research and development program to bridge the gap between existing systems and those which would be economically viable, and discuss the implications of such a program for federal research and manufacturing support policies.

### Characteristics of Current Commercial IR Detectors

Current commercial IR imaging systems do not satisfactorily meet the needs of end-users. This is true of detectors, cameras, and of entire systems, including associated electronics and software. Much better performance and power are being demanded than current systems allow. Many end-users complain that current systems lack sufficient resolution and sensitivity. Officials of commercial detector firms told us that their IR cameras and full systems would have wider appeal in every field of application if they could increase resolution and sensitivity without sacrificing scan rates or cost. Other end-users find current IR systems too cumbersome. And virtually all end-users state that current systems are too expensive to be appealing to a wide variety of industries and firms.

Military research gave impetus originally to single point lead salt and germanium detectors in the 1970s, allowing for high-volume and inexpensive production of those photodiodes for commercial applications. But neither first generation Common Modules nor second generation focal plane arrays have fully entered the commercial market, except for police surveillance and reconnaissance, and a few "showcase" models sold by commercial firms for other uses. This is because components of many IR systems are still classified and, in the case of second generation IRFPAs, military producers recognize that more fundamental materials and producibility advances are necessary before spin-offs become possible. Firms in the commercial market therefore have relied on older and simpler single-point scanning technologies for most applications. Although Common Modules and second generation IRFPAs would be much better suited for advanced commercial applications, firms continue to modify older technologies to fit modern needs.

The vast majority of existing commercial units are based on lead sulfide (PbS), lead selenide (PbSe), or germanium (Ge), all of which have low sensitivities. Lead salt photocapacitors account for about two-thirds the commercial IR market, with annual sales in 1991 of about $20 million. PbS and PbSe cells are photoconductive semiconductors because their resistance changes upon application of incident infrared radiation. Compared to other types of detectors used in the same wavelength range, lead salt-based detectors have a lower sensitivity but can be used at room temperature. (Commercial detectors typically use a single stage thermo-electric cooler to stabilize the detector's temperature, however.)

Lead salt-based detectors are used extensively in process spectroanalysis and for non-contact temperature measurement and control in manufacturing industries ranging from pharmaceuticals, to paper, metal, and foods. They can be used to detect the temperature on crackers, for instance, while baking in an oven, to ensure that the optimum temperature is maintained. Lead sulfide detectors are also used to detect carbon monoxide and hydrocarbons in automobile emissions. Lead selenide is used in medical breath analyzers to detect $CO_2$ and other gases, and in fire detectors. These detectors, like Germanium-based ones, are not used in scanning IR cameras because they do not offer the inherent sensitivity and speed necessary; that task is accomplished by PtSi-, InSb- and MCT-based systems.

Germanium (Ge)-based detectors have the second largest commercial market share, with about $7 million in 1991 sales (23 percent). Germanium-based photovoltaic detectors usually consist of a mesa-type diode structure, operate at room temperature, and use single stage TECs for temperature stability. These detectors are used commercially to focus lasers, and to measure the quality of laser transmissions through fiber optical cable. Germanium's detectivity is about $1 \times 10^{11}$, which is offset by poor quantum efficiency and poor resistivity.

A third type of existing commercial detectors is PtSi-based. These detectors accounted for about five percent of the market, $1.5 million, in 1991, since firms have only begun recently to market PtSi-based detectors. Although PtSi has a low quantum efficiency, many firms are betting heavily on its success in taking over applications from other types of IR detectors. Most importantly, visible light CCDs are now used extensively in machine vision systems, which are used in automated process control, and PtSi could extend their capabilities into the infrared. The two advantages of PtSi detectors are that large arrays are possible (512x512 is standard, with 1,024x1,024 routinely possible), and that systems are inexpensive. Both are possible due to the mature, silicon-based integrated circuit technology upon which PtSi is founded.

PtSi CCDs have both a lower responsivity than MCT- and InSb-based detectors and also a slower speed of screen update. These factors limit its range of potential applications. Several manufacturers are working to overcome these barriers, however, and infrared CCDs based on PtSi may be formidable competitors to MCT for many segments of the commercial market.

Indium antimonide (InSb)-based detectors will compete with MCT-based detectors for the commercial applications requiring greater sensitivities. InSb-based detectors, like Ge-based ones, make use of the photovoltaic effect, in which a voltage is generated upon the application of infrared energy. InSb's detectivity, 2 x $10^{10}$, is close to MCT's, (1 X $10^{10}$). Like MCT, InSb needs to be cooled to cryogenic temperatures. InSb's major limits are in quantum efficiency, and resistivity, in which it is overtaken by MCT. InSb-based detectors are also limited generally to high temperature applications, e.g. viewing jet engine plumes, process control of hot metals, or predictive maintenance of moving parts or electrical components, because they operate in the two to five micron range. InSb arrays are approximately the same size as MCT arrays, and, in fact, many commercial IR firms, such as Inframetrics, Amber, and Santa Barbara Focalplane, can integrate either MCT or InSb arrays into the same readout circuitry and camera.

Currently, commercial IR cameras typically employ single-point capacitors as their detectors. Altogether, about 80 percent of current commercial IR revenues, and 95 percent of the units sold, are derived from single point, low performance detectors. In fact, detectors made with PbS, PbSe, and Ge do not generally come in linear or staring configurations because they do not offer the inherent sensitivity which is the reason for using larger arrays. When single photodiodes and photocapacitors are placed in scanning IR systems, the scanner spends so little time on any given pixel that the sensitivity is much worse than if the detector were staring. IR detectors based on these slower, less efficient, and less sensitive materials are suitable for a many low-performance applications, but they do not achieve the accuracy and responsivity required for the sophisticated applications described in part two.

Even cameras and other commercial IR systems which seek to achieve video-size images continue to use single-point arrays. These systems must trade-off between sensitivity (which can be improved by increasing the time a detector pixel stares at an object) and scan speed (which is improved by having the scanning pixel spend less time on any given point). The best systems, from Inframetrics and Amber, generally claim about 0.1°C resolution at video rate scanning, but sacrifice image size, which falls to about 190 X 190 for Inframetric's new Model 760.[57] Bales Scientific's TIP thermal system is typical of this trade-off in alternative characteristics, offering either 24 frames per second with 0.2°C sensitivity, or six frames a second with .0125°C thermal resolution. Radiometric applications, in which absolute temperature is measured, are difficult to fulfill unless scanning rates reach near real-time speed (≥30 frames/ second) with good sensitivity (≤0.1°C).

Currently available commercial IR detectors which do offer scanning or staring arrays with greater sensitivities and quicker scan speeds are very expensive, and also "cumbersome" because they require high-maintenance cryocoolers. It is typical for advanced commercial IR systems, with a camera, computer hardware, and advanced software, to cost at least $100,000.

[57] Many users told us, however, that in real-world practice, Inframetric's and Amber's systems do not reach 0.1°C.

The best detector suites, including their dewar-cryocooler components, can account for less than two-thirds the total cost; $60,000 in the case of a 320 X 256 InSb array manufactured by Santa Barbara Focalplane.

Cryocoolers and dewars are a major cost component, and also a leading reason why commercializers of scanning and staring IR detectors have been restricted, by and large, to laboratory environments. Cryocoolers also have a shorter mean time to failure than the best alternative, TECs, and therefore have higher maintenance costs, as well. Many older systems, moreover, manufactured by Amber Engineering, FLIR systems, Bales Engineering, and Inframetrics, use open-cycle cryocoolers, which require frequent topping off with liquid nitrogen. This requires a source of liquid nitrogen, usually from a tank. Bales Engineering's system requires up to six gallons of liquid nitrogen to run effectively. These kinds of devices are not portable and require a skilled technical user who can transfer nitrogen into the system when it runs low.

Commercial manufacturers are beginning to move away from open-cycle cryocoolers to closed-cycle or Stirling coolers. Inframetrics leads the market in cryocooler innovation. It recently introduced a new closed cycle cooler which is an option on the 500 series of commercial radiometers, and is built into the new model 760 radiometer. Both systems utilize single point MCT-based scanning detectors. The closed-cycle cooler has been standard equipment for several years on Inframetric's night vision products, but only recently has been incorporated into the company's commercial products. Electrically-powered, the cooler employs Stirling cycle engine principles to accomplish its task of generating liquid nitrogen temperatures in less than five minutes. Small enough to hold in one's hand, the cooler draws very little electrical power and weighs less than one-half pound.

As Inframetrics describes it, the Stirling cycle engine is basically a compression-expansion refrigerator with no valves; instead, a regenerator is incorporated. The regenerator is a length of porous material which has a low thermal conductivity to maintain a temperature gradient, restricted flow to maintain a pressure gradient, and a high heat capacity to act as a highly efficient heat exchanger. The regenerator, located between a reciprocating piston and the cold well, moves back and forth in synchronization with the piston. During the compression phase, the cold well volume is initially small. The regenerator then moves to increase the cold well volume. Pressurized helium gas bleeds through the regenerator to fill the cold well. As the gas bleeds through, it is pre-cooled by the regenerator to near liquid nitrogen temperature. The piston then moves to the expansion phase lowering the gas temperature to 77°K or lower. Finally, the regenerator moves to decrease the volume in the cold well, forcing the cold helium back up through the regenerator and the cycle begins again.

Amber Engineering and Agema Infrared have also begun to advertise products with a closed-cycle Stirling cooler option, and both FLIR Systems and Bales Engineering, according to company officials, will replace their open-cycle cryocoolers with closed-cycle ones. In biomedical applications and non-destructive testing of materials, where lab technicians may maintain the IR system, liquid nitrogen cooling may be acceptable because the nitrogen can be kept nearby. But in the vast majority of applications, in plant/factory diagnostics, non-destructive testing of IC boards, building maintenance, aerial overflights, etc., there is no time or space to reach for liquid nitrogen refills. Portability is essential for perhaps 75 percent of the units sold; units for process control are the only major area where this is not a major issue. Systems which require cumbersome and hazardous liquid nitrogen refills have been slow to find widespread commercial audiences, and producers are adamant about switching to closed-cycle coolers.

In summary, two major design limits currently hinder IR systems from gaining broad commercial use and sales. First, existing systems offer relatively low performance since they are often single point photodiodes of materials with low detectivity. In such systems, constant trade-offs between scan rate and sensitivity must be made, limiting the system's overall performance. The models which do overcome this barrier are far too expensive to gain widespread use. Secondly, the more advanced commercial systems are very expensive in both investment and maintenance costs, and are typically not very portable. The more widespread use of closed-cycle cryocoolers will ease this latter problem, but not eliminate it all together.

Characteristics of Future Commercial IR Systems

Manufacturers interested in developing infrared detectors with dual-use potential must have a clear idea of the traits which would make such systems attractive in the future commercial market, some of which differ significantly from traits of current military systems. Eight such performance characteristics are essential: absolute temperature measurement, portability and light weight, video output, simple voltage operation, minimal linear drift, a rapid rate of image update, short-range capability, and statistical software packages. The final and dominant characteristic is lower cost, which is discussed separately.

Absolute Temperature Measurement. IR imagers which can determine absolute temperature in every pixel are called *radiometric*, and the majority of sophisticated IR systems bound for commercial markets will need this property. Those applications include biomedical thermography, NDE of IC boards, NDE of materials for defects, weld control, monitoring of heat changes, predictive maintenance, remote sensing for scientific research, and counternarcotics reconnaissance. Absolute temperature measurement is a boon to, but not a prerequisite for entering the markets for web inspection, food inspection, underground remote sensing, environmental crisis evaluation, and pipeline and gas leak detection. The only potential applications which would not benefit from imagers with radiometric qualities are the NDE of buildings and structures, police surveillance, drivers' vision enhancers, IVHS components, and airplane enhanced vision systems. These are also the applications in which imagers are sent straight to viewers without any manipulation by software; they are mostly straightforward viewing applications.

The radiometric requirement has not caused design problems for IR systems which use single point detectors, or simple arrays, because the exact behavior and bias of each individual pixels can be known. With staring systems, however, which frequently have over 80,000 pixels, it becomes costly to test each pixel and install corrective electronics on each individual detector chip to compensate for non-uniformities. The only way to avoid the expense of corrective electronics, according to executives with whom we spoke, is to build pixels more uniformly. This is a crucial materials issue for both commercial and military detectors; producibility research should offer payoffs in both sectors.

Among the commercial producers, Amber Engineering has a reputation for designing IR systems for radiometric, absolute temperature applications, and has advanced electronics for correcting non-uniformities, and therefore sells the most expensive systems on the market, costing about $185,000 each. Amber's Pro-View system is designed to correct for non-uniformities in real time to produce a highly uniform displayed image, according to company officials. Although Amber's system uses less elaborate gain and offset correction equipment than do IR detectors for the military market, Amber's system offers the best radiometric equipment now available in the commercial sector. Other companies actively developing staring systems with radiometric qualities are Bales Scientific, Inframetrics, Agema, and FLIR systems.

Portability and Light Weight. Many commercial IR systems need to be compact and light weight so that they can be portable and readily transported to the work site. This is especially true for applications in predictive maintenance, non-destructive testing, surveillance, and transportation.

In predictive maintenance applications, for example, the operator would walk through a factory or energy plant and test mechanical/electrical components for indications of maintenance needs, such as hot wear-spots, cold spots from air in-leakage, and increased resistiveness, using a shoulder-portable unit which should weight no more than about 20 pounds. Most existing IR units for predictive maintenance already weigh just under 20 pounds, including the IR detector, image screen, and battery pack. For example, Inframetrics uses a modularly designed system for its Model 740, which is specifically designed for predictive plant maintenance. The 740 allows the camera to be mounted on a tripod while the control module remains with the operator, who can view the built-in display and store images on the integral disk drive.

FLIRs for the surveillance and underground imaging markets also need to be lightweight, in this case about 10 pounds, because they are mounted on rotating turrets, and because every pound counts on helicopters and small aircraft. Weight is also an issue, although not paramount, in the transportation sector, where about 30 pounds would be the limit. In such applications, compact cameras would be mounted on vehicles' roofs or under their hoods, while the processing electronics would be buried under the hood, and images would be transmitted to the cabin for viewing. Like machines designed for predictive maintenance, imagers for the non-destructive evaluation of buildings and structures have to be portable and shoulder-mounted, and thus require compact and light weight equipment.

Video Output. Video output is necessary for every one of the applications we have described. In most cases, this is because data are being recorded on videotape while being viewed by users on television screens; this process is called videography. Videographic signals could be in the format of RS-170, RS-343, digital RS-170, or direct 12-bit pixel data. In some cases, infrared videography supplies a documentary record which can be replayed later; in other cases, it provides raw digital data which becomes the basis for statistical analyses. Straightforward videotaping is sufficient for some applications in biomedical thermography, for the NDE of buildings and structures, for predictive maintenance, environmental crisis evaluation, NDE of pipelines and gas leaks, and surveillance. Raw digital data form the basis for statistical comparisons in more advanced applications in biomedical thermography, NDE of materials for defects, process control, underground remote sensing, scientific research in remote sensing, and counternarcotics reconnaissance. (Some application areas could require either video or raw digital data outputs depending on the specific use being made of the IR device.) The only applications in which video recording hook-ups would not be necessary are the driver's vision enhancer, IVHS components, and airplane EVS; in those instances images would be seen directly on a TV-screen and not recorded.

Simple Voltage Operation. Portable systems need to operate on conventional voltages, either from a wall socket or from a battery pack; the commercial standard uses a 12 VDC supply. Among the applications which could more easily make use of IR systems if they could be hooked up to standard electrical sockets are those in biomedical thermography, the non-destructive evaluation of IC boards and other materials for defects, and almost all forms of process control. Other commercial IR systems need to work from portable battery packs, such as applications in predictive plant maintenance, NDE of buildings and structures, and remote sensing. In several other applications, IR systems would operate off vehicles' own power, and would therefore need to use as little energy as possible; this holds true for drivers' vision enhancers, IVHS componen·, airplane EVS, and inspections of roads and power lines.

Linear Drift. Linear drift has plagued attempts by several firms to develop staring detectors for commercial applications. Linear drift is defined as a shift in the responsivity and resistivity of pixels over time. Pixel variances in two-dimensional arrays are corrected right after manufacturing, but many pixels continue to change as they are used. This is one of the largest hurdles to overcome, according to commercial producers, if systems employing staring IRFPAs are to gain commercial market share. Frequent system recalibration has been the solution proposed by many of the commercial system designers we contacted, but this reduces the speed at which images can be acquired. A much better solution, which is a top priority for MCT-based military systems, is to manufacture stability and linearity right into the system. This involves improvements in IR materials, specifically in wafers for substrates and epitaxial growth, and in indium bump bonding.

Image Update Rate. The rate at which images are updated is also an important characteristic for commercial applications. Generally, systems should plan to operate from 30Hz to 60Hz, offering video rates. Such performance is essential for some applications in biomedical thermography, and for IC Board Inspection, NDE of buildings and structures, weld control, predictive maintenance, remote sensing for scientific research, underground remote sensing, environmental crisis evaluation, pipeline and gas leak detection, surveillance, and transportation. Other applications require even faster frame rates: The diagnosis of neurological, circulatory, and pain disorders by thermography systems, for example, requires imagers operating at 1 MHz, as does the NDE of materials for defects. Systems for web inspection, whether on metal, plastic, fabric, or food-inspection lines, should work at least at 1.2 MHz. Moreover, systems designed for these high-speed markets are also required to have sensitivities of at least 0.1 NEDT.

The most effective means of achieving rapid screen rates, coupled with strong sensitivities, is to use second generation focal plane arrays. Photoconductive infrared devices, whether single point or linear, cannot approach high update rates and maintain satisfactory levels of sensitivity. All the commercial models on the market which use scanning and SPRITE-style arrays offer trade-offs between sensitivity and speed of screen update. Since most systems use single-point InSb or MCT photodiodes or photocapacitors to produce images above 320 X 240 in size, that single detector can only spend a millisecond on any one pixel. The faster the scan rate, the less time spent on each pixel. Sensitivity must now be sacrificed for the sake of image speeds; hence the preference for staring arrays, which can provide both acceptable screen update rates and adequate sensitivity.

Short-range Capability. Another desirable characteristic, short range capability, is more a matter of optics than detector design. Most military systems are designed to function at ranges from 7,000 meters to a few hundred feet, where they are used, of course, as either weapon sights, navigational aids, missile seekers, or early warning equipment on satellites. Many commercial applications, however, require crisp resolution from only a few feet away, for example biomedicine, NDE of IC boards, weld control, web inspection, food inspection, and predictive maintenance. Infrared microscopes are even used sometimes, for example, to inspect IC boards. On the other hand, transportation and law enforcement applications would require FLIRs with intermediate ranges (400 feet), while remote sensing and counternarcotics reconnaissance applications require military-range optics of several kilometers.

This short-range requirement implies that infrared detectors operating in the MWIR may be sufficient to meet most performance parameters. LWIR detectors have long been preferred by the armed services for long-range applications such as search and track, missile guidance, and pilot's vision aids. But this is because IR detectors in the MWIR generally deliver significantly lower performance then LWIR detectors when imaging at several kilometers. For many dual-use applications detectors operating in the MWIR may be more than adequate and, as will be seen below, would be much less expensive.

Software Design. The most important characteristic of commercial systems, after the IR detector itself, is the software design. Competitive advantage in several markets for commercial detectors will be determined by the crispness and efficiency of IR images, and by the sophistication of the software used to manipulate data. The only three areas of application which do not require advanced software are the NDE of buildings and structures, police surveillance, and transportation. In those applications, images would be viewed directly and interpreted subjectively by the human operator, without needing to be analyzed. The visual contrast between areas of different temperatures, presented on a video screen, is enough to fulfill the requirements of these applications.

For all other applications, software packages that accompany IR camera systems currently conduct two broad types of statistical comparisons. Some systems compare thermal profiles of a viewed object with an accepted standard, or with other units of like design. It is assumed that if extraneous factors are factored out, such as variations in ambient temperature, emissivity, or humidity, any object of a particular type will have an identical thermal profile every time, identical with any like object, unless it has been altered for one reason or another. Applications which would use this statistical comparison, for example, are found in the NDE of IC boards, Although early systems made *qualitative* comparisons, and did not measure absolute temperatures, the trend is towards using radiometric data. "Extraneous factors" are often so numerous, and so common, that absolute temperature readings (and complex software processing of data) are necessary to factor out such complications.

The second type of statistical comparison is to follow the same specific object over several months to determine if its heat profile has changed. In the case of motors, for example, this technique could show gradual overheating from poor lubrication, rust, clogging, or misalignment; in electrical components, it could show the buildup of resistance in circuitry. In humans, it could show that a skin graft has gained vascularity and is alive, or could diagnose the development (or healing) of neurological or vascular diseases.

Quantitative, radiometric versions of these statistical methods will undoubtedly gain wider use at the expense of the older, qualitative methods previously used. Without radiometric readings, engineers can only compare one area in a picture with another subjectively, and can not be sure that an object is really "hotter" or "colder". They can not precisely compare pictures taken from one object with pictures from another, or compare thermal profiles of an object taken over time. Radiometric readings take out any doubt in temperature comparisons.

Table 14 below summarizes the performance characteristics desirable for infrared devices for each area of application covered.

Table 14. Detector Characteristics Desired for Commercial Applications

| APPLICATION | IMAGE SIZE | SENSITIVITY | SCAN RATE | RANGE | RADIOMETRIC | POTENTIAL FOR MCT-BASED |
|---|---|---|---|---|---|---|
| Biomedical Thermography | Large Area 2-D | <0.1°C | >60Hz | <5 ft | ✓ | High |
| Non-Destructive Evaluation | | | | | X | |
| IC Board Inspection | Video Resolution 2-D | >0.1°C | 60 Hz | < 1 ft. | X | High |
| Buildings & Structures | Video Resolution 2-D | 1-2°C | 30 Hz | 10-100 ft. | X | Low |
| Materials for Defects | Video Resolution 2-D | <0.1°C | 1 MHz | 1-10 ft. | ✓ | High |
| Predictive Maintenance | | | | | | |
| Electrical | Video Resolution 2-D | 0.1°C | 30 Hz | 1-20 ft. | ✓ | High |
| Mechanical | Video Resolution 2-D | 0.1°C | 30 Hz | 1-20 ft. | ✓ | High |

| APPLICATION | IMAGE SIZE | SENSITIVITY | SCAN RATE | RANGE | RADIOMETRIC | POTENTIAL FOR MCT-BASED |
|---|---|---|---|---|---|---|
| Process Control | | | | | | |
| Weld Control | <100x100 | 0.1°C | 60 Hz | 1-5 ft. | ✓ | High |
| Web Inspection | Linear (1x180+) | 0.1°C | 1.2 MHz | 1-2 ft. | X | High |
| Monitor Heat Changes (chemicals, glass, plastics, metals, wafers) | Video Resolution 2-D | <0.1°C | 30 Hz | 1-10 ft. | ✓ | High |
| Food Inspection | Linear (1x180+) | 0.1°C | 1 MHz | 1-2 ft. | X | Medium |
| Remote Sensing | | | | | | |
| Scientific Research | Large Area 2-D | 0.1°C | <30 Hz | From space | X | High |
| Underground (contaminated & toxic waste, graves, aquifers) | Large Area 2-D | 0.1°C | 30 Hz | 1,000-3,000 ft. | X | High |
| Environmental Crisis Evaluation | Large Area 2-D | 0.1°C | 30 Hz | 1,000-3,000 ft. | X | High |
| Pipeline & Gas Leaks | Video Resolution 2-D | 0.1°C | 30 Hz | 1,000-3,000 ft. | X | Medium |

| APPLICATION | IMAGE SIZE | SENSITIVITY | SCAN RATE | RANGE | RADIOMETRIC | POTENTIAL FOR MCT-BASED |
|---|---|---|---|---|---|---|
| Surveillance | | | | | | |
| Police (search & rescue, law enforcement) | Video Resolution 2-D | 0.1°C | 30 Hz | 100-1,000 ft. | X | High |
| Counternarcotics Reconnaissance | Video Resolution 2-D | 0.1°C | 30 Hz | 1,000 ft.-6 miles | X | High |
| Transportation | | | | | | |
| Driver's Vision Enhancer | Video Resolution 2-D | 0.1°C | 30 Hz | 1200 ft. | X | Low |
| IVHS Components | Video Resolution 2-D | 0.1°C | 30 Hz | 1200 ft. | X | Medium |
| Airplane Enhanced Vision System | Large Area 2-D | 0.1°C | 30 Hz | >2,600 ft. | X | High |

Cost. Cost considerations will dominate the rate at which second IRPAs enter commercial markets. Tables 15-17 summarize the costs of current IR systems, in three categories: single point detectors, multi-element arrays, and IR camera systems. The tables are based on a survey of all major producers, domestic and foreign, and prices are averaged across manufacturers. As will be evident, the current prices of systems with advanced capabilities are greater than can be sustained by a significant market.

Single Point Detectors. Prices for single point detectors increase in proportion with the sophistication of the infrared sensitive material used, and in proportion to the variety of cooling equipment used. Although bare, single photodiodes are sold by many commercial infrared firms, the value-added products are those which integrate detector suites and cameras, along with accompanying electronics, computer hardware and software, and such auxiliarty components as printers or extra lenses.

Multi-Element Arrays. Multi-element arrays manufactured for commercial markets experience yield and producibility problems to a lesser extent than their military counterparts, but costs still increase in geometric proportion to array size. Arrays using sophisticated IR materials, such as InSb or MCT, cost typically over ten times more than lead-salt and germanium products.

Complete IR Systems. These imagers integrate IR devices as the vital component in an entire IR system, which also includes, typically, a video terminal, a stand-alone computer, extensive analytical software, lenses with varying focal lengths, and sometimes printing machines. Prices may be misleading, since much of the cost difference between systems is caused by computer hardware and software costs, rather than detector choices. A general rule of thumb appears to be that the infrared detector suite accounts for one-third the cost of the complete IR system.

**Table 15. Single Point Detectors**

| Material | System | Detector Configuration | Cooling Requirements | Average Price |
|---|---|---|---|---|
| PbS | Detector Alone | Single Diode | Uncooled | $60 |
| | " | " | 1st Stage TEC | $558 |
| | " | " | 2nd Stage TEC | $509 |
| | " | " | Glass Dewar | $1,447 |
| PbSe | Detector Alone | Single Diode | Uncooled | $98 |
| | " | " | 1st Stage TEC | $585 |
| | " | " | 2nd Stage TEC | $562 |
| | " | " | Glass Dewar | $1,194 |
| Ge | Detector Alone | Single Diode | 1st Stage TEC | $275 |
| | " | " | 2nd Stage TEC | $450 |
| | " | " | Glass Dewar | $1,800 |
| | " | " | 2nd Stage TEC | $807 |
| InSb | Detector Alone | Single Diode | 2nd Stage TEC | $2,818 |
| | " | " | 3rd Stage TEC | $3,333 |
| | " | " | Glass Dewar | $3,551 |
| MCT | Detector Alone | Single Diode | 2nd Stage TEC | $740 |
| | " | " | 3rd Stage TEC | $3,333 |
| | " | " | Glass Dewar | $3,333 |
| | " | " | Metal Dewar | $3,813 |

Table 16. Multi-Element Arrays.

| Material | System | Detector Configuration | Cooling Assembly | Average Price |
|---|---|---|---|---|
| PbSe | Detector Alone | 16 X 1 | Uncooled | $1,359 |
| | " | 128 X 1 | Uncooled | $5,298 |
| PbS | Detector Alone | 4 X 1 | TEC | $918 |
| | " | 16 X 1 | Uncooled | $1447 |
| Ge | " | 16 X 1 | Uncooled | $768 |
| | " | 128 X 1 | Uncooled | $4,250 |
| | " | 2 X 2 | Uncooled | $311 |
| InSb | " | 16 X 1 | Metal Dewar | $15,742 |
| | " | 4 X 4 | Metal Dewar | $15,742 |
| | " | 128 X 128 | Metal Dewar | $35,000 |
| | " | 320 X 256 | Metal Dewar | $60,000 |
| MCT | " | 5 X 1 | Metal Dewar | $6,000 |
| | " | 8 X 1 | Metal Dewar | $8,783 |
| | " | 228 X 4 | Metal Dewar | $20,000 |

Table 17. Costs of IR Systems Based on Various Materials

| Material | Detector Configuration | System Cost |
|---|---|---|
| InSb | SPRITE single | $90,000 |
| | 128 X 128 | $95,000 |
| | 320 X 240 | $99,000 |
| PtSi | 512 x 512 | $49,000 |
| MCT | SPRITE single | $83,500 |
| | 60 X 1 | $55,000 |
| | 256 X 256 | $185,000 |

These advanced IR cameras on the commercial market are expensive for two major reasons. First, companies which produce multi-element IR cameras consider them to be "showcase" pieces, and do not expect to sell them in large numbers in the mid-term. Firms are either waiting for detector prices to fall, or are using their top-of-the-line detectors as demonstration pieces intended only for high-end users, such as laboratory-based researchers in industry or government, nuclear power plant maintenance engineers, or counternarcotics agents. Many commercial firms said that military-style FLIRs would cost several hundred thousand dollars if they were to be offered commercially; estimates ran as high as $750,000.

Second, advanced IR systems are very new to the commercial market in which systems dominate which are still based on single-point detectors. Prices may drop somewhat as manufacturers perfect their products. Nearly every executive we interviewed said that portable and inexpensive staring IR cameras have been eagerly awaited by the commercial IR industry, but that systems were not yet feasible at marketable prices.

Threshold Costs. A new generation of high performance commercial cameras would not only need to possess the performance features discussed earlier in this section, but would have to sell at prices which are considerably lower than current models. The size of the potential market will naturally grow as systems fall in price, but the prices listed in table 18 below represent thresholds at which systems could find viable markets.

**Table 18. Threshold Prices for Commercial Applications**

| Application | Estimated Price |
|---|---|
| Biomedical Thermography | $50,000 |
| Non-Destructive Evaluation | |
| IC Board Inspection | $60,000 |
| Buildings & Structures | $20,000 |
| Materials for Defects | $50,000 |
| Process Control | |
| Weld Control | $80,000 |
| Web Inspection | $80,000 |
| Monitor Heat Changes (chemicals, glass, plastics, metals, wafers) | $75,000 |
| Food Inspection | $75,000 |
| Predictive Maintenance | |
| Electrical | $75,000 |
| Mechanical | $75,000 |
| Remote Sensing | |
| Scientific Research | $200,000 |
| Underground (contaminated & toxic waste, graves, aquifers) | $50,000 |
| Environmental Crisis Evaluation | $50,000 |
| Pipeline & Gas Leaks | $50,000 |
| Surveillance | |
| Police Law Enforcement | $125,000 |
| Counternarcotics Reconnaissance | $125,000 |
| Transportation | |
| Driver's Vision Enhancer | $1,000 |
| IVHS Components | $10,000 |
| Airplane Enhanced Vision System | $100,000 |

## Market Summary

Table 19 below summarizes the potential commercial markets for sophisticated infrared focal plane arrays if they were to reach threshold costs. Altogether, over 200 applications could be available, mostly within the next five years, and IRFPAs could be components in a diverse assortment of cameras and imagers in markets worth over $2 billion.

## Table 19. Commercial Markets for IRFPAs

| APPLICATION | TIME TO MARKET (YEARS) | FEASIBLE UNIT PRICE | # UNITS SOLD/ YEAR | MARKET VALUE | COMMENTS |
|---|---|---|---|---|---|
| Biomedical Thermography | 3-5+ | $50,000 | 6,000 | $300 million | Scanning machines exist, but none high-performance staring |
| Non-Destructive Evaluation | | | | | |
| IC Board Inspection | 2-3 | $60,000 | 4,000 | $240 million | " |
| Buildings & Structures | 1-2 | $20,000 | 1,000 | $20 million | " |
| Materials for Defects | 0 | $50,000 | 500 | $25 million | Staring machines exist, but very expensive |
| Predictive Maintenance | | | | | |
| Electrical | 2-3 | $80,000 | 5,000 | $400 million | Staring systems too expensive |
| Mechanical | 2-3 | $80,000 | 5,000 | $400 million | " |

| APPLICATION | TIME TO MARKET (YEARS) | FEASIBLE UNIT PRICE | # UNITS SOLD/ YEAR | MARKET VALUE | COMMENTS |
|---|---|---|---|---|---|
| Process Control | | | | | |
| Weld Control | 2-3 | $75,000 | 300 | $23 million | Currently in research |
| Web Inspection | 1-3 | $75,000 | 3,000 | $225 million | Many companies fielding early systems |
| Monitoring Heat Changes (chemicals, glass, plastics, metals, wafers) | 3-5 | $75,000 | 2,500 | $188 million | In company development |
| Food Inspection | 3-5 | $75,000 | 500 | $38 million | Scanning systems in research |
| Remote Sensing | | | | | |
| Scientific Research | 0 | $200,000 | 50 | $10 million | Staring systems exist |
| Underground (contaminated & toxic waste, graves, acquifers) | 2-3 | $50,000 | 400 | $20 million | Scanning systems exist, staring systems too expensive |
| Environmental Crisis Evaluation | 2-3 | $50,000 | 200 | $10 million | " |
| Pipeline & Gas Leaks | 1-2 | $50,000 | 600 | $30 million | " |

| APPLICATION | TIME TO MARKET (YEARS) | FEASIBLE UNIT PRICE | # UNITS SOLD/ YEAR | MARKET VALUE | COMMENTS |
|---|---|---|---|---|---|
| Surveillance | | | | | |
| Police (Search & Rescue, Law Enforcement) | 0 | $125,000 | 450 | $56 million | Staring systems exist |
| Countemarcotics Reconnaissance | 0 | $125,000 | 200 | $25 million | " |
| Transportation | | | | | |
| Driver's Vision Enhancer | 2-4 | $1,000 | 100,000 | $100 million | In research phase |
| IVHS Components | 5+ | $10,000 | 1,000 | $10 million | In government-funded research |
| Airplane Enhanced Vision System | 3-4 | $100,000 | 400 | $40 million | Staring systems used in industry resarch |

Ten specific areas of application, of the 19 distinct categories which have been discussed, are the most promising for MCT-based focal plane arrays. All these areas of application require high-performance detectors, whether judged by scan rate, sensitivity, or density of pixels required; each category also could make use of fairly expensive systems, although they would still have to be less expensive than military sensors.

First, applications in web inspection require detectors which operate at up to 1.2 Hz while maintaining sensitivities better than 0.1°C. MCT-based focal plane arrays could fulfill these parameters more effectively, and at lower cost, than existing systems and competing materials. Additionally, since the *linear* detectors required for web inspection would be smaller and less complicated than mosaic focal plane arrays, second generation IRFPAs may have a good chance of meeting the price target of $75,000 in this application. Moreover, several end-users stated they were willing to pay up to $150,000 to be among the first to purchase IR inspection systems for their web production lines, so initial market entry may be even easier. Automated inspection systems for metal, rubber, textile, and plastic web production lines are just now beginning to gain appeal in industry, and linear, staring infrared cameras have been judged by many manufacturers of automated inspection systems as the best choice.

A second prospective application now in the initial stage of development is the monitoring of heat changes in manufacturing processes with infrared focal plane arrays. A broad range of firms in the chemical, pharmaceutical, semiconductor, and injection molded plastic and metal industries are keenly interested in experimenting with IR technologies to regulate the rate, uniformity, and exact temperature of cooling or warming processes. Rather than monitor heat changes in the chamber in which a chemical reaction takes place, or at select points along a mold, for instance, focal plane arrays would profile the entire temperature of the reactants or plastic components themselves. MCT-based focal plane arrays would be ideally suited in these applications because the throughput required, and thus speed at which images would need to be acquired, would demand sensitivities greater than 0.1°C, and scan rates greater than 30 Hz. Focal plane arrays also could provide the large density of pixels preferred by system integrators who either desire a great deal of detail in small areas (when imaging semiconductor wafers, for example) or large fields (in large chemical reactions). Moreover, price would not be as severe a constraint in this process control application, as it would be in some others.

Third, the performance characteristics of focal plane arrays are tailored to the needs of predictive maintenance of both electrical components and mechanical parts. Detectors for those applications would need to be radiometric to make quantitative comparisons between the state and predicted lifetime of components. They should also offer large fields of view, which would expedite inspections of large pieces of equipment such as switchboxes and machinery gears. MCT-based SPRITE detectors now prevail in this market, since neither PtSi-, nor lead salt- nor vidicon- based detectors offers the inherent performance necessary. Affordable IRFPAs have long been awaited by the predictive maintenance community.

Fourth, electronics firms have expressed a keen interest in integrating focal plane array-based IR detectors into inspection systems for IC boards. IR detectors now play a role in assessing the heat load and distribution in prototypes, in damaged boards, and in occasional quality control checks. But it is only recently that quality control engineers have proposed integrating infrared inspection systems as full-time process control instruments. Given the high throughput of electronics assembly-lines, requiring systems operating at 60 Hz, the need for vide-sized images, and sensitivities below 0.1°C, MCT-based focal plane arrays may find a strong potential in this market.

Fifth, the non-destructive evaluation of advanced materials such as composites, laminates, and coatings is an area in which MCT-based IRFPAs could move in the next five years from laboratory-style inspections to automated assembly line inspection. Such systems require both extreme sensitivity (better than 0.1°C) and high scan rates (1MHz in the case of inspecting aging aircraft). Focal plane arrays can easily meet the performance parameters required, which are more demanding than in nearly any other sector, at costs that the industry is prepared to pay.

Sixth, biomedical thermography would require high-performance, high-sensitivity focal plane arrays with large pixel densities (about 356x256). Although the medical community retains a negative perception of IR thermography, the far greater capabilities of second generation IRFPAs could eventually result in a large potential customer base. As in the process control and NDE markets, cost constraints would not be as narrow as in other applications.

Seventh, infrared cameras for surveillance also could be a profitable market for IRFPAs based on MCT. Since the applications are outdoors, and often image areas in excess of one kilometer, especially when used in aerial overflights, MCT-based detectors could achieve the sensitivity and clarity of picture not available with other IR sensitive materials. With feasible prices exceeding $100,000, and with less processing software requirements than other applications, cost constraints would not be as difficult to meet. End-users in both law enforcement and counternarcotics are familiar with IR technology, demand high performance devices, and, if threshold prices could be reached, would be a ready, albeit medium-volume market.

Eighth, passenger and cargo airlines are eager to install enhanced vision systems so that pilots can land in Category Three airports amid rain, fog, mist, and other obscurants which now often delay flights and caus monetary losses. With a price target of $100,000, airplane EVS systems would be the second most expensive application, meaning they could be a relatively early step into the commercial IR market for second generation focal plane arrays. Both infrared detectors and milimeter wave radar systems could satisfy system designers, however, and it is yet uncertain which technology will prevail.

A ninth area of application that may be particularly well-suited for MCT-based detectors is underground remote sensing. The dual-band IR technique, used by researchers at the Lawrence Livermore National Laboratory, employs two IR detectors simultaneously, one in the MWIR, the other in the LWIR. MCT-based detectors are the only advanced IR material capable of performing in both wavelengths. The other technique proposed for this application, joint IR/GPR inspection, employs MCT-based detectors in the LWIR. As in other areas of application, end-users are keenly interested in acquiring or even testing second generation focal plane arrays, knowing that such imagers would expedite their work and increase the precision with which they conduct surveys.

A tenth area of potential application suitable for MCT-based detectors is environmental crisis assessment. Both dual-band MWIR and LWIR systems of MCT-based detectors and LWIR and UV bands have been used for experimental applications in this sector. MCT-based detectors offer the best resolution, sensitivity, and scan rate necessary for such applications, and system designers have therefore used them from the start. Although the overall market is limited, it is a nearly certain market for MCT-based detectors.

Altogether, these ten markets for which MCT-based detectors appear best suited, could be worth $1.8 billion per year, or over three quarters the projected total annual commercial market for IR detectors. The likelihood that manufacturers of MCT-based detectors will be able to seize these opportunities is more dependent on their ability to meet threshold costs than to meet required performance requirements, because second generation military arrays have already surpassed most performance needs of the commercial markets. The crucial need is to reduce the costs of second generation focal plane arrays for dual-use applications.

## Cutting Costs in MCT-based IR Detectors with Dual-Use Potential

If MCT-based focal plane arrays are to fulfill their dual-use potential, their costs must be reduced substantially. This is feasible, and we outline below seven recommendations for continuing research which could achieve significant cost reductions. These proposals are all achievable in a reasonable period of time. They are based on in-depth interviews with individuals working in the commercial, defense, and university sectors of the IR community, and on a broad survey of the literature available.

First, to succeed commercially, MCT-based detectors must incorporate less expensive cooling components. Accounting for up to 90 percent of the cost of detector suites manufactured for the military, cooling subsystems appear to be the components with the greatest potential for reduced costs. There are two ways to accomplish this: either by reducing the cost of conventional cryocoolers, or by abandoning them in favor of thermo-electric coolers.

Cryocoolers could be made less expensive either by standardizing their designs, or by inventing better designs based on new principles. DoD's SADA program already proposes to create a family of four standardized cryocooler-dewar assemblies to accommodate various military detector arrays. This program is predicted to decrease the cost of detectors by one-half in the mid-term. If such modularly-designed, second-generation cryocoolers were made available commercially, they would easily drop several thousand dollars off the cost of thermal imagers.

On the other hand, far cheaper cryocoolers costing less than $1,000, and boasting of effective lifetimes in excess of 100,000 hours, may become a reality in the long run. The cryogenic needs of the C-MOS and superconductor industries, in particular, may indirectly result in the development of better cryocoolers for IR sensors because they promise a market in the tens of thousands by about 1996. To meet this demand, several manufacturers are coming out with cryocoolers which use less power and are more reliable than their forebears, and cost a good deal less. For example, Carriers, Inc. is said to be coming out with a five to ten watt 80°K cooler. A joint product-development effort of Superconductor Technologies Inc. and Sunpower is also prototyping a cryocooler which cools to 80°K at four watts. Both new cryocoolers are predicted to have lifetimes exceeding 5,000 hours and to cost just over $3,000, if produced in large numbers.

In the near-term, commercial infrared firms favor Twin-Opposed Piston (TOP) linear Stirling coolers, developed by DoD funds, as the best option for commercial applications. As explained previously, Stirling coolers are favored increasingly by firms such as Amber, Inframetrics, and Agema, which produce high-end commercial IR imagers. Stirling coolers cost $3,000, and while more expensive than the promise of the new systems, represent a reasonable compromise for the next few years, especially if compared alongside the older and cumbersome open-cycle cryocoolers.

A second way to cut cooling costs is to use TECs instead of cryocoolers. There was a near consensus among those we interviewed that this would definitely be the way to go, and the commercial market is already heading in this direction. Cryocoolers limit the portability of IR detectors because they drain batteries too fast, and require refilling if they are in frequent use; they are also more expensive than TECs. If TECs were substituted for cryocoolers, about $5,000 to $10,000 could be saved on every system, compared with systems currently using open-cycle cryocoolers. The main drawback of TECs, of course, is that they can not now, and may not soon be able to, achieve liquid nitrogen temperatures, limiting their use to IR materials that can operate at temperatures closer to 170°K.

The second recommendation follows logically: Since the 3-5 micron variety of MCT-based detector can operate at TEC temperatures, researchers should concentrate on commercial applications that can make use of this bandwidth. Tradeoffs between MWIR and LWIR detectors are hotly debated by defense officials, but the commercial market appears to have no preference between them for most applications. LWIR detectors are used for extremely sensitive military applications because the 8-12 micron window offers longer wavelengths and substantially more energy than the MWIR, 3-5 micron window. This is crucial in sensitive applications in space or on targeting systems, for instance, where the range of view is typically over six kilometers. LWIR detectors were designed especially to see through weather obscurants and battlefield smoke, rain, haze, or high humidity.[58] The MWIR band, but comparison, offers substantially less energy, which gives detectors a poor signal-to-noise ratio, making imaging more difficult amid battlefield obscurants. This is a major reason why the Army, Air Force, and DARPA have not stressed research on MWIR detectors.

This entire debate is much less pronounced in the commercial market, where systems operating in both the MWIR and LWIR are sold generally for identical applications. All else being equal, moreover, focal plane arrays operating in the MWIR could offer satisfactory performance at a more affordable price because they would not require cryocoolers. Even if some performance were sacrificed in switching to MWIR from LWIR detectors, infrared sensors using focal plane arrays would offer so much better performance than current commercial systems, that the loss would be unlikely to be considered significant.

The Thermal Weapon Sight program is unique among military applications, according to officials we contacted, because it could have worked either with TEC-cooled MWIR, or cryocooled LWIR, MCT-based detectors. Thermo-electrically-cooled MCT-based detectors were finally chosen, according to defense officials, because they achieved sensitivity of 0.1°C at lower cost. Similarly, commercial producers are a lot less concerned with the greater energy available to detectors operating in the LWIR, and more concerned with gaining sufficient performance at a far lower price. Given the clear commercial preference for cost savings over performance beyond a certain point, LWIR detectors may only find a niche in the most sensitive applications, and those in which fog, mist, and obscurants are common: web inspection, surveillance, scientific research remote sensing, airplane enhanced vision systems, laboratory-style non-destructive testing, monitoring heat changes, and biomedical imaging. If MWIR detectors can be produced more cheaply than LWIR detectors, as is predicted, they will capture the bulk of the

[58] The Navy, on the other hand, uses detectors in the MWIR because it contends that the 3-5 micron bandwidth is better for spotting along the ocean, towards the horizon, without obscurants. They contend that contrast improves at shorter wavelengths. For instance, the MWIR at a 300°K background temperature has over twice the relative contrast than the LWIR band. This allows naval FLIRs to recognize smaller objects, from greater distances, sooner.

market in thermal imagers. That includes applications in IC board inspection, food inspection, predictive maintenance, remote sensing, driver's vision enhancement, and IVHS components. In the remote sensing market, where several competing techniques are going after the same applications, LWIR and MWIR detectors could be combined in dual-band techniques for underground sensing, environmental crisis evaluations, and pipeline and gas leak detection, but MWIR detectors may be favored in the back-scatter radiometry and IR/GPR techniques.

Third, research needs to be pursued in basic producibility and materials issues. Next-generation infrared detectors are still beset by three fundamental problems: background saturation, non-uniformity effects, and fabrication problems. There would be more than ample payoff in both the military and commercial sectors if infrared detector chips could be made more cheaply. Executives of commercial companies whom we interviewed supported research on wafer uniformity and size for both substrates and epitaxial layers, alternative substrates, testing for improved producibility, indium bump bonding, modeling, automation, device architecture, and passivation.

An essential producibility issue cited by many executives interested in dual-use IR detectors is increasing the uniformity of CZT and MCT wafers, because this determines the noise and non-uniformity in the eventual detector. Uniformity ought to be built into IR detector systems, they contended, rather than tested in. Since non-uniformities in MCT-based detectors has been attributed mainly to defects in the CZT layer, substrate research is an essential component in producibility research. This could reduce testing needs, increase yields, make systems more uniformly sensitive, and reduce gain and offset correction requirements.

Commercial firms have been battling non-uniformities, and they argue that this is one of the major reasons they have shied away from larger arrays. Non-uniformity hinders sensitivity, accuracy, and reliability of commercially-available large-array IR system. Agema's Infrared offers the most sensitive systems on the market, with a measurement accuracy of one percent and repeatability of 0.5 percent regardless of the ambient environment. Agema's systems have less than one percent non-uniformity. The other leading commercial firms, FLIR systems, Inframetrics, Amber, and Bales, offer systems with over two or three percent non-uniformities. AGEMA has gotten around basic producibility issues with its SPRITE detectors with a sophisticated clamping system using two integrated black bodies and four temperature sensors. Their systems, however, are among the most expensive available, topping $185,000.

The importance of MCT for military applications has stimulated extensive work on the growth and study of bulk and thin epitaxial layers. That research will benefit commercial firms seeking to market second generation, MCT-based detectors, executives say. The bulk-grown material still suffers, however, from many problems such as Te inclusions, high dislocation densities, stress-induced defects, and lateral and vertical compositional nonuniformities. Recent producibility efforts on MCT and CZT are all worthwhile, and should continue, according to commercial producers. Epitaxial growth of CdTe or lattice matched CZT substrates by liquid phase epitaxy (LPE), vapor phase epitaxy (VPE), molecular beam epitaxy (MBE), and metal-organic chemical vapor deposition (MOCVD) techniques are all necessary research areas on both commercial and military agendas.

Another essential producibility issue is to improve the indium-bump process. According to those we surveyed, the long term use of commercial IR detectors, and their repeated cooling and warming, could compound connection problems between substrate and epitaxial layers. Many executives we interviewed indicated that one of the first portions of hybrid focal plane arrays to fail, if the IRFPA is used long term, are the indium bump bonds. This is due to asymmetrical warping, over time, of either substrate or epitaxial material. A comprehensive dual-use program could expand basic research into indium bump disjunction.

Moreover, executives stressed that producibility studies should be expanded to incorporate two related detector technologies. First, they suggested that producibility research should emphasize MCT-based detectors which operate in the MWIR because of its greater commercial potential. DoD's producibility program is generally focused on MCT arrays optimized for the 8-12 micron region, and thus only indirectly benefits commercial IR technologies. Second, producibility programs should concentrate on detectors closest to the commercial ideal: video-resolution (356x240) staring detectors, or at least scanning or TDI or SPRITE detectors which offer that resolution at over 30 Hz (in some cases, near to 1.5 MHz), are radiometric, and are sensitive to a 0.1°C change in temperature. Detectors which currently are the focus of producibility research are not of this size, nor are the linear ones optimized for commercial scan rates and sensitivities.

A fourth recommendation is to develop integrated packages of all the auxiliary components necessary for IR detectors, which are now usually produced separately. These components include the amplifier, A/D converter, video converter, video screen, and optical train. Several producers said the commercial market would find military IR detectors more attractive if optics could be manufactured in plastic, and if the amplifier, A/D converter, and video converter could all be bought in one inexpensive, integrated electronics package. Many individuals said that by relaxing hard-to-achieve specifications, and by demanding systems at lower costs, the Department of Defense could encourage such inexpensive integration of auxiliary components. For instance, the Driver's Vision Enhancer program, which plans to procure about 20,000 units for about $2,000 each, should have this effect on producers. Systems designed for the DVE will probably use plastic optics, integrate auxiliary electronics, and use commercially available, low-cost, flat-top video displays.

The fifth cost-cutting recommendation is to increase the production rate of military programs to make possible economies of scale. Second generation IR detectors have only been produced in small batches in laboratory-style environments; they have not been produced in high volumes. Executives contend that if military programs were to make possible high-volume assembly lines, then costs could be cut drastically as overhead were amortized over a broader base and non-recurring processes were phased out. A high volume production environment would encourage automated testing, batch production, insertion into packaging, and other economies of scale. It should also minimize recurring labor costs. Production and testing could be accomplished in batches, rather than the piece-meal manner common at laboratories. This is especially applicable to the growth of substrates and epitaxial layers, and to their testing.

The sixth recommendation for cost reduction is to standardize infrared detectors produced for defense in a manner similar to the Common Modules. Naturally, any standards should take account of the needs of commercial end-users as well as military requirements, such as video-size staring arrays sensitive to at least 0.1°C and operating nominally in the MWIR, cheaper cryocoolers, long life, and so forth. The SADA program is such a standardization program, but it does not reflect commercial needs, as explained earlier.

The Defense Department successfully standardized the Common Modules during the 1970s and 1980s. That program developed a core set of standardized IR scanning detectors of 60, 120, and 180 elements, which could be mixed and matched and married to a wide variety of objective optics modules, eyepieces, TV cameras, and other specialized modules. Basic modules included the scanner, detector/dewar, IR imager, visual collimator, cryogenic cooler, preamplifier, post-amplifier, auxiliary electronics, bias regulator, scan/interlace electronics, and light emitting diode (LED) array. From about 1976 to 1985, when purchases of Common Modules were completed, unit costs had dropped from $60,000 to $5,000. The Army reports that it saved $902 million by purchasing 79,000 Common Modules for 16 weapon systems, instead of permitting each weapon system to utilize a unique IR detector. The same approach to second generation IR detectors, if made available commercially and taking account of commercial needs, would benefit the commercial market as well as the military.

It appears likely that the Army, in particular, is heading toward standardizing second-generation FLIRs. The Army's "Battle Labs," a one-year old technology initiative which aims to speed Army weapon development and acquisition while reducing unit costs, is considering ways to maximize commonality for second generation FLIRs to be used by both ground vehicles and aircraft. The Army believes it could save $1 billion with standardization.

In the past, of course, each weapon system was developed virtually from scratch, and the only duplication occurred when the same firms were contracted for more than one IR system. This "stove pipe" approach, for example, resulted in Bradley fighting vehicles and M1 series tanks being equipped with different second generation FLIRs. The "Battle Labs" task force is expected during 1993 to formulate a strategy which finds common ground in the two vehicles' FLIRs, as well as those to be placed in the RAH-66 Comanche helicopter and the M109A6 155mm self-propelled howitzer. A draft request for proposals for the FLIR was scheduled at the time of this writing for release in August 1993, and a contract is planned to be awarded by April 1994, horizontally integrating cutting edge night vision advancements.

The final recommendation is to recognize that if excessively challenging military specs were eased, IR detectors could be produced for a fraction of their cost, greatly advancing their attractiveness in the commercial market. In addition to the specifications for IR sensors, certain mil-specs are applied to all integrated circuits and further drive up IR system costs. The two most demanding types of military specifications appear to be those pertaining to operability requirements and to testing. By demanding excessively high uniformity in IR materials, the military has directly lowered yields. As IRFPAs are required to operate near-perfectly, nearly pure materials are required. The extreme difficulty in producing such uniform materials, and especially the controls required to ensure such purity, drive up costs. The Javelin program, in particular, demonstrated the high cost associated with overly demanding operability requirements.[59]

The pixel operability demanded for military IR systems is typically over 99 percent. By comparison, producers of commercial IR devices and systems integrators told us they would easily settle for 95-97 percent operability. Although no one would estimate the potential cost savings with relaxed defect specifications, indications are that detectors could be at least 20 percent cheaper with a reduction of a few percentage points in pixel operability.

The second excessively demanding mil-spec is testing. Manufacturers of both military and commercial detectors seek rapid and accurate, but cost effective, testing regimes. Several officials of defense contractors told us that DoD's testing requirements are excessively stringent: testing of every pixel is required at the wafer level, and at the cryogenic die level.[60] The DoD's justification for this, understandably, is that the success of an entire weapon system, such as a guided missile, hinges on the performance of its IRFPA. IRFPAs for the commercial markets do not require testing regimes that are nearly as rigorous. In the past, 95 percent of testing had been performed manually, and the greatest bottlenecks in IRFPA production have been at the cryogenic wafer testing. The executives we interviewed were nearly unanimous that mil-specs

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[59] In the 64x64 seeker IRFPA, the four baseline specifications were:

(1) No defective pixels in the center 6x6 elements of the array
(2) Six or less defective pixels in any 3x3 element area
(3) Less than 200 defective pixels in any 32x32 area, and
(4) Less than 400 defective pixels in the entire array

[60] There is testing, for instance, for die voltage current functioning, responsivity, RMS Noise, D-Star, defects, fixed pattern voltages, etc.

for IRFPA testing drive costs significantly higher than would be possible in commercial applications, and would not be necessary, either.

In conclusion, infrared focal plane arrays could find applications in commercial systems which may reach a $2.2 billion market in five years. Applications with a potential market value of $1.8 billion are the most likely candidates for the use of MCI-based systems; lower cost materials are more likely to be used for the remainder of the commercial applications. IRFPAs offer several advantages over existing commercial systems, such as radiometric properties, rapid scan rate, large resolution, light weight, and durability. While current military programs will advance focal plane array technologies with dual-use potential, they can not ensure such uses because both system costs and performance specifications differ significantly between the military and commercial markets. Federal support for infrared focal plane array technology development could be easily amended to develop IR's dual-use potential, however.

## Implications for Federal Technology Policies

Based on the foregoing analysis, it seems clear that federal programs to encourage the development of lower cost infrared materials can bear important dividends both for the competitiveness of American industry in commercial markets and for the affordability of essential defense capabilities. Existing DARPA and service development programs have already produced impressive technical results that make it possible to contemplate the wide range of dual-use applications of advanced IR systems described in this report. Additional programs focused directly on stimulating the fulfillment of advanced IR systems' dual-use potential, as described in the previous section, could accelerate the rate at which these applications are introduced. Our analysis, moreover, has several broad implications for federal technology policies.

First, it is evident that mechanisms should be established through which the government can set priorities in technology development and coordinate the efforts of the various agencies that promote research and development so that they can act collaboratively in pursuit of those priorities. While it would be a mistake to create a single agency charged with technology development, it is essential that the various players pursue their individual efforts toward a common set of goals, and in recognition of a shared roadmap. This will become increasingly important as the Department of Commerce's National Institute of Standards and Technology receives substantially larger amounts of funds, as is now planned. Relevant congressional committees should be consulted in drawing up this overall technology development plan.

Second, it appears that federal support for cooperative industrial efforts may be the most effective means of encouraging rapid advances in dual-use applications. Given the limits on available federal funds, the greatest leverage may be obtained by packaging federal support in ways that encourage new cooperative ventures. Two kinds of cooperative arrangements may be particularly worthwhile:

- Joint ventures of defense manufacturers and companies that currently operate primarily in the commercial sector could be synergistic, mating the advanced technical capabilities of the defense industry with the market savvy of the commercial enterprises.

- The creation of vertically-integrated manufacturing consortia also could be beneficial, combining materials producers, camera manufacturers, IR system integrators, and end-users in cooperative enterprises intended to exploit advanced technical capabilities in particular manufacturing sectors with dual-use potential.

Third, the Defense Department should move expeditiously to implement the commitment expressed by Deputy Defense Secretary William Perry to shift from "a regulation-based system to a market-based system." Dr. Perry identified certain DoD practices as major impediments to realization of the commercial potential of IR and other defense technologies, and thereby to the improvements in DoD costs and capabilities that could result from such greater integration of defense and commercial industries. Among the most important barriers, he noted, are certain cost-accounting and pricing requirements, excessive oversight and auditing practices, excessively demanding military specifications, technical data requirements, various socio-economic and other source requirements, and commercially unacceptable subcontractor requirements.\[61]

Concrete steps by the Department of Defense to relax these requirements could significantly assist defense manufacturers to reduce the cost of infrared materials, cameras, and systems, facilitating their introduction into dual-use markets.

[61]/ Testimony of William Perry before the House Armed Services Committee (June 15, 1993).